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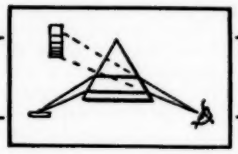

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THE OPTICAL SOCIETY OF AMERICA was organized in 1916 "*to increase and diffuse the knowledge of optics in all its branches, pure and applied, to promote the mutual interests of investigators of optical problems, of designers, manufacturers and users of optical instruments and apparatus of all kinds and to encourage cooperation among them.*" It aims to serve the interests of all who are engaged in any branch of optics from fundamental research to the manufacture of optical goods.

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All changes of address of members of the Optical Society of America should be communicated to the Secretary, Professor Arthur C. Hardy, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Journal of the
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Editorial Comment: Report of the Colorimetry Committee

FOR the past ten years the Colorimetry Committee of the Optical Society of America, under the chairmanship of Dr. Loyd A. Jones, has been laboring diligently on a report designed to bring order into the definitions and concepts of color, and to provide useful data. The Society expects to publish this report, when completed, in book form, amply illustrated and well supplied with color plates, so that it will be available to the far-flung groups of workers concerned with matters of color.

Owing to conditions which prevent immediate completion and publication, it has been deemed desirable to publish in the Journal from time to time certain completed portions of the report, with the purpose of exposing them to critical comment before final issuance, and to make readers of the Journal acquainted with progress to date. In the present issue the Editors have pleasure in presenting a survey of the historical background and general evolution of the report by the Chairman of the Colorimetry Committee, followed by a discussion of "The Concept of Color" which forms Chapter II of the report. Chapter I, consisting of a popular and non-technical introduction to the science of color, cannot be published satisfactorily in the Journal because of the extensive use in it of color plates.

Publication of portions of the material now available should prove useful because of the current urgent need for much of the data, and because of the unifying influence on work in the field of color which the report should exert. It is hoped that the availability of those portions of the Report which will be published in the near future will render unnecessary any further proliferation of make-shift and partial solutions of color problems under pressure of the emergency.

The Committee will welcome comments and suggestions for improvement which may be utilized in the final edition of the Colorimetry Report.

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The Historical Background and Evolution of the Colorimetry Report

LOYD A. JONES
Chairman, Colorimetry Committee

THE Optical Society of America has recognized, ever since its organization in 1916, an obligation to contribute to the advancement of the theory and practice of optics. The preparation, from time to time, of reports dealing specifically with particular topics of pure and applied optics constitutes a partial fulfillment of this obligation. These reports have been prepared by groups of individuals recognized as leaders in their particular fields and chosen so as to represent as equitably as possible the various points of view within each field. Typical of such committee activities are the reports of the committees on spectrophotometry[1] and radiometry,[2] and the earlier report on colorimetry.[3]

In addition to such committee reports, the semi-annual meetings of the Society and the *Journal of the Optical Society of America* stimulate activity in all of the fields of theoretical and applied optics. The science of color has received unprecedented impetus from all of these activities of the Society. The interest of the Society in the science of color has been so genuine and continuous that the meetings of the Optical Society now provide the chief forum in America for the discussion of problems of color vision, methods of color measurement, and related subjects. At the semi-annual meetings of the Society a full half-day session is almost invariably devoted to the reading and discussion of a full program of contributed papers on color and closely related subjects. Such sessions always attract a large and receptive group of members and friends of the Society. The formal and informal discussions stimulated by these sessions make accessible a depth and range of experience in color science otherwise unobtainable in America. In addition to encouraging such sessions, the Society frequently arranges symposia of invited lectures on color and closely related subjects. Outstanding among recent programs of this sort were the symposia on Color Standards, Photoelectric Spectrophotometry, and Color Specification, in 1931; on Measuring Spectral Radiation in 1934; on the Physical Basis of Sensation in 1935; on the Optics of Vision in 1939; on Color Measurement in 1941; and on Visual Processes and Anomalous Color Vision in 1943.

The most important results of current research in color vision and color measurement have appeared in frequent articles in the *Journal of the Optical Society of America*. The Journal, therefore, constitutes a rich source of information concerning color, both in the files of past years and in current issues. The first result of a recent expansion of the editorial policy of the Journal was the publication, in December, 1940, of a series of five co-ordinated articles concerning as many independent investigations of different aspects of the Munsell color system. A similar series of co-ordinated papers originally presented at a symposium of the Inter-Society Color Council, entitled Color in Art Education, was published in the December, 1942, issue of the Journal. Three of the papers presented at the symposium on Color Blindness, arranged for the 1943 Winter Meeting of the Optical Society by the Inter-Society Color Council, were published as a series in the June, 1943, issue of the Journal. Further examples of simultaneous and co-operative publication of the results of independent researches in other divisions of the science of color may be expected to appear occasionally. Such carefully planned publication serves to minimize the misunderstandings and resolvable differences of opinion which have made the evaluation of much of the older literature of the science of color so difficult.

A unique accomplishment, sponsored by the Optical Society of America, the translation and publication in English of Helmholtz' *Physiological Optics*, contributed as much to the advancement of the science of color as to any other one branch of optics.

[1] "Spectrophotometry, report of O.S.A. Progress Committee for 1922–3," J. Opt. Soc. Am. and Rev. Sci. Inst. **10**, 169 (1925).
[2] "Report of the Progress Committee on Radiometry and Photometry," J. Opt. Soc. Am. and Rev. Sci. Inst. **11**, 357 (1925).
[3] "Report of Committee on Colorimetry for 1920–21," J. Opt. Soc. Am. and Rev. Sci. Inst. **6**, 527 (1922).

The Optical Society aided greatly in the establishment of the Inter-Society Color Council, an organization for the exchange of information and consultation on problems of color between many of the national scientific and engineering societies. Thus, in all of its regular activities, and in many special undertakings, the Optical Society of America has fostered and will continue to contribute outstandingly to the advancement of the science of color.

During 1920 and 1921 a Committee on Colorimetry,* under the chairmanship of Dr. L. T. Troland, prepared a report designed to set forth a clear terminology in the field of colorimetrics, to summarize the then available physical, psychophysical and psychological data relating color to its stimulus conditions, to outline briefly the principal methods of color measurement, and to establish the relationship between their respective scales. This report, which was published in the August, 1922,[3] issue of the *Journal of the Optical Society of America and Review of Scientific Instruments*, proved to be an extremely valuable contribution to the literature of the subject. We feel that it may be said without exaggeration that, at the time of its publication, it represented the most complete and authoritative compilation of material in the field of colorimetrics. It stood for many years as the outstanding reference authority. The present Committee wishes to take the opportunity to pay tribute to Dr. L. T. Troland and to Mr. I. G. Priest, who were the two individuals most directly responsible for the preparation of the 1922 report. While other members of the committee contributed to some extent by advice, counsel, and the preparation of data, it was Dr. Troland who gave most generously of his time and thought in the preparation of that report, and who actually wrote by far the major portion thereof. In that work he was most ably assisted by Mr. Priest, who was in constant touch with Dr. Troland throughout the period during which the report was being prepared. Mr. Priest assembled the major portion of the tables containing numerical data, proofread copy with his usual meticulous care, and must be credited with contributing many of the ideas which helped to shape the general character of the report. His contribution certainly is second only to that of Dr. Troland.

It was recognized some years ago that a revision of the 1922 report was badly needed. Subsequent to 1922 much progress had been made by investigators in this field both in this country and abroad. In 1931, at a meeting of the International Commission on Illumination held in England, an agreement was reached which established the characteristics of the standard observer for the purposes of color measurement, this standard being expressed in the form of numerical data defining the trichromatic distribution functions for the average normal human eye. Also at this meeting, by international agreement, the characteristics of three light sources, Illuminant *A*, Illuminant *B*, and Illuminant *C*, for use in the specification of color, were agreed upon. Moreover, during the decade following the publication of the 1922 report, much research work was done on many problems in the field of colorimetrics, thus making available more voluminous and more precise data relative to the relationship between the physical stimulus and the resultant subjective response. In short, satisfactory as it was at the time of publication, the 1922 report required considerable revision and amplification by 1932. Consequently, the Optical Society, through its Committee on Colorimetry, undertook the preparation of a new report which, it is hoped, will likewise serve as an authoritative as well as a modern reference work on this subject.

As emphasized at the beginning of this discussion, the Optical Society has maintained an active interest in the subject of color and colorimetry throughout the years following the publication of the 1922 report. Committees on colorimetry have been in existence throughout the entire period, and some of these committees have done excellent work in crystallizing opinion concerning color terminology in scientific, industrial, and artistic circles, and have collected valuable information for use in the preparation of a revised and improved report. Results of the work of these committees have not been published but have been collected and passed on to succeeding committees. The present committee

* The personnel of this committee was: L. T. Troland, *Chairman*, I. G. Priest, E. A. Weaver, L. A. Jones, H. E. Ives.

wishes to acknowledge its indebtedness to these committees which have gone before it and which have functioned so efficiently.

The present Committee* came into being in 1933 and since that time has been working toward the preparation of a revised and expanded report. In undertaking this work it was necessary to decide in what manner, if any, the 1922 report should be modified. It was apparent, of course, that many of the numerical data contained in the 1922 report should be superseded by the newer and more precise information which had become available during the years since its publication, and that the results of research work carried out since 1922 should be added in order to increase the value and utility of the report and to bring it up to date. Moreover, we were faced with the necessity of deciding whether the general style and mode of presentation should be modified and if so in what direction. But further than this, and of much more vital importance and of much greater difficulty of decision, was the fundamental question of the possibility of a radical modification in the basic concept of color, which, of necessity, must be expressed in the definition of that term.

At the first meeting of the Committee, held in the early part of 1933, practically the entire discussion related to the organization of material and the general type of the report. The Committee was in practically unanimous agreement that the 1922 report appealed almost entirely to specialists in the field of colorimetrics. It was agreed that the chief criticism of the 1922 report had come from persons having considerable interest in the subject of color and colorimetrics but not prepared by training or inclination to read a report couched in highly technical language. The number of persons whose potential interest in color and color science could be aroused by a suitably written discussion is believed to be very great. The Committee was, therefore, convinced that this report, in order to be of maximum usefulness to all of these groups of readers, should contain not only all of the specialized discussion and data required by the specialist in this field, but also a discussion sufficiently elementary and interesting to attract and hold the attention of casual readers, and a gradual transition from that introduction into the more advanced exposition. The present report has been prepared with these objectives in view. In the earlier chapters a rather lengthy, and somewhat elementary, discussion of the general principles of color and color measurement will be given. In this treatment, precision of statement possibly may have been sacrificed to some extent for the sake of simplicity. If the reader finds in these chapters some statements which lack exactness and perhaps savor of half-truths, it is hoped that he will be lenient and look to later chapters for a more precise and meticulous treatment.

In the 1922 report color was defined as follows: "Color is the general name for all sensations arising from the activity of the retina of the eye and its attached nervous mechanisms, this activity being, in nearly every case in the normal individual, a specific response to radiant energy of certain wave-lengths and intensities." Thus color was defined as a sensation and hence as a purely subjective concept. At the time the 1922 report was written sensation was regarded by many psychologists, and particularly by those concerned with the preparation of that report, as a very definite and meaningful element of experience and consciousness. However, even at that time the literature of psychology contained some criticism of the concept represented by the word sensation. In fact, in 1893, William James, professor of psychology at Harvard University,[4] stated: "It is impossible rigorously to *define* a sensation; and in the actual life of consciousness sensations, popularly so called, and perceptions

* As organized in 1933, the committee personnel was: L. A. Jones, *Chairman*, E. Q. Adams, C. Bittinger, H. P. Gage, K. S. Gibson, I. H. Godlove, A. C. Hardy, H. E. Ives, D. B. Judd, E. M. Lowry, A. E. O. Munsell, Miss D. Nickerson, M. Rea Paul, W. B. Van Arsdel. Since 1933 some additions to the personnel have been made. These additions were made in some cases at the request of individuals who felt that they would like to serve on the committee, in some cases at the suggestion of other members of the committee, and in still other cases because of the desire of the chairman to bring into the committee certain individuals who, he felt, could materially assist in the work. At the present time the committee personnel is as follows: L. A. Jones, *Chairman*, E. Q. Adams, Mrs. Blanche R. Bellamy, C. Bittinger, E. C. Crittenden, C. Z. Draves, C. E. Foss, H. P. Gage, K. S. Gibson, I. H. Godlove, A. C. Hardy, D. B. Judd, E. M. Lowry, M. Luckiesh, D. L. MacAdam, S. M. Newhall, Miss D. Nickerson, B. O'Brien, M. R. Paul, Miss L. L. Sloan.

[4] William James, *Psychology* (H. Holt and Company, New York, 1893), p. 12.

merge into each other by insensible degrees. All we can say is that *what we mean by sensations are* FIRST *things in the way of consciousness*. They are *immediate* results upon consciousness of nerve-currents as they enter the brain, and before they have awakened any suggestions or associations with past experience. But it is obvious that *such immediate sensations can only be realized in the earliest days of life*. They are all but impossible to adults with memories and stores of associations acquired," and further, "a pure sensation we saw above, page 12, to be an abstraction never realized in adult life."

During the past two or three decades this kind of criticism of the concept of sensation has continued to appear in the psychological literature. Some psychologists regard the concept of sensation as of very little use. We find Troland, in 1930, writing as follows: "Such writers as McDougall and Hollingworth have practically eliminated the facts of sensation from their textbooks."[5a] However, three of the latest and most authoritative general textbooks[6–8] feature both sensation and perception and have separate chapters or sections on each. These and other recent works indicate that sensation has come to be recognized by psychologists as the relatively constant and fundamental core or limit toward which perceptions may approach. It is for this very reason that the concept of sensation is useful and important. The more interpretative or meaningful a perception is, the more different from pure sensation; the more sensory or uninterpretative the experience, the closer approximation to pure sensation. The receptive apparatus seems to be built for sensation, and the concept of sensation is indispensable in describing the sensory function.

Early in the deliberations of the present committee some members suggested that the definition of color should be altered from the form given in the 1922 report so as to define color as a perception rather than as a sensation. Such a course involved revision of the statement as to the attributes of color which, in the 1922 report, were defined as hue, saturation, and brilliance. On a perceptual basis the modes of appearance of color should logically be considered as additional attributes. Thus Troland[5b] in a chapter dealing with visual perceptions says: **"Other Color Attributes.**—Hue, saturation and brilliance do not exhaust all possible attributes of colors, since it is possible for them to vary in dimensions distinct from any of these three. . . . Other color attributes which are of importance in perceptual studies include the so-called 'modes of appearance,' or *Erscheinungsweisen*. Thus, color may appear as 'body,' 'surface,' or 'film.' They may also be lustrous or non-lustrous. We shall consider these 'modes,' with their psychophysical relations, in the next Section." In the next section under the caption **"Seven 'Modes' of Color 'Appearance'"** he discusses the perceptual aspects of film, luminosity, and glow, bulky, plane transparent, mirrored, and luster modes of appearance. He then concludes this section with the following statement: "The seven different modes of appearance of colors which we have considered above, are strictly phenomenal or experiential attributes, not reducible to physical terms, and demonstrable only by introspection. However, as we have seen, the conditions for their presence in consciousness can be specified objectively, if we assume the response system to be normal in its other stages." In the next section[5c] he states: **"Properties of Opaque Surface Colors.**—However, the commonest 'mode' still remains to be considered. This is the *opaque surface* character, and is determined, psychophysically, by reflecting objects having matt, or highly diffusing surfaces. Such opaque visual surfaces carry most of the typical color phenomena of everyday experience, and hence are worthy of particular attention."

David Katz[9] in his book published in 1935, which, it is stated in the introductory pages, deals specifically with the perceptual aspects of color, treats the same modes of appearance as

[5] L. T. Troland, *Psychophysiology* (D. Van Nostrand Company, New York, 1929). (*a*) Vol. II, p. 8; (*b*) Vol. I, p. 254; (*c*) Vol. I, p. 262; (*d*) Vol. II, p. 57.

[6] R. S. Woodworth, *Psychology* (H. Holt and Company, New York, 1940).

[7] Boring, Langfeld, and Weld, *Introduction to Psychology* (John Wiley and Sons, New York, 1939).

[8] E. G. Boring, *Sensation and Perception in the History of Experimental Psychology* (Appleton-Century, New York, 1942).

[9] David Katz, *The World of Colour*, an abridgment of the second German edition of 1930 translated by R. B. MacLeod and C. W. Fox (Kegan Paul, Trench, Trubner and Company, London, 1935); (*a*) p. 17.

those mentioned by Troland with the exception that his translator uses the term *volume color* rather than *bulky color* appearing in Troland's terminology. These eight modes Katz classifies under the general caption of spatial modes of appearance. At a later point in his treatment he implies that there are certain temporal modes of appearance such as sparkle and glitter, although he does not specifically include these as modes of appearance. Katz[9a] also quotes from Gelb as follows: "Gelb remarks in one place that perhaps the doctrine of the attributes of sensation will have to undergo a reconstruction to take into account the modes of appearance of color. With this I am in agreement." At another point Katz states (p. 57): "The fact of most immediate importance is that different modes of appearance of the *same color* are all based on the same retinal processes." (Italics are ours.) Now it would seem, from a consideration of the last two quotations, that even the modern psychologist who would restrict the significance of sensation to an almost meaningless abstraction must, at times, fall back upon the concept in the discussion of certain of the perceptual aspects of color, and, moreover, that while he advocates the addition of modes of appearance to the attributes of color he admits that the *same color* may have different modes of appearance. This is interpreted by the chairman as an implied admission that the mode of appearance does not change color *per se*, and that the concept of sensation is useful.

In a manuscript submitted to the Committee by one of its members who vigorously advocated the adoption of the perceptual point of view in the definition of color, this statement appeared, "Following the terminology developed in recent investigations of visual appearance by psychologists a system of classifying color has been worked out under the following classes: aperture color, illuminant color, volume color, and surface color," and at a later point in the discussion the attributes of visual appearance required for the specification of each of these color modes are given. In the case of surface colors, one of the most common modes of appearance, it is indicated that a specification of hue, saturation, lightness, transparency, and glossiness must be given in order to define completely the perceptual characteristics of such a color.

Thus it is apparent that in the case of certain modes of appearance it would be necessary to increase the number of attributes from three to five, or possibly, if the more extreme position of the Gestalt school of psychology be taken, to more than five. This would follow provided certain temporal modes of appearance, such as glitter, sparkle, flicker, etc., are considered to be necessary.

The chairman believes he is correct in stating that the Committee did not react favorably to the proposal to define color as a perception. The opinion of the majority seemed to be that such a definition would include so many attributes not usually associated with color as to be unsuitable in a report on colorimetry. This opinion, of course, reflects in no way unfavorably upon the usefulness and the desirability of a careful study of the perceptual aspects of color including modes of appearance. Such studies are undoubtedly of great value and should not under any circumstances be excluded from discussion and treatment even in the report of this Committee.

Following a careful consideration of the consequences of a perceptual point of view, the attention of the Committee turned again to the definition of color given in the 1922 report. Color was there defined as a sensation and a suggestion was made that possibly this definition could be revised so as to make it acceptable to all members of the committee by specifically limiting color to include only the non-spatial and non-temporal characteristics of visual sensation. This would definitely limit the attributes required for the specification of color to the three attributes discussed in the 1922 report.

The modified definition of color as a sensation, with limitation to non-spatial and non-temporal attributes, was not acceptable, either to those who doubt the usefulness of the concept of sensation or to those whose concern is primarily with the physical and instrumental problems of colorimetry. The latter group felt that so long as color is defined as a sensation, it cannot be measured by physical instruments or by procedures reconcilable with physical principles of measurement. However, the Committee as a whole did not feel that such criticism was entirely justified since the acceptance of a few

simple assumptions makes possible measurements of sensation according to established psychological methods. However, the measurement of color, as it is practiced at the present time, is admittedly not a purely psychological measurement, nor, on the other hand, are such measurements purely physical.

This discussion continued for more years than the chairman likes to remember and a stalemate seemed to have been reached within the committee between the physical and psychological viewpoints. While this discussion of the basic philosophy of the report was in progress, proposals were formulated for a simplified and rational terminology of limited scope. In 1937 a short preliminary report[10] was published because the magnitude of the task of preparing the complete report as planned indicated the probability of a long delay in its appearance. The chairman therefore wished to make public some account of the work of the Committee prior to 1937 to indicate the status of the report and to introduce the nomenclature almost unanimously agreed upon by the Committee.*

This preliminary report contained a list of terms relating to radiometric and photometric quantities and certain general recommendations on the use of word endings, such as those of reflection, reflectance, and reflectivity. These recommendations were accepted without formal ballot by the Committee. Of particular importance was the Committee's decision to recommend that the word "luminosity" be substituted for "visibility" with reference to the ratio of luminous flux to radiant flux. This change was in conformity with the action of other groups, particularly in the field of illuminating engineering. A somewhat more radical change, but in the opinion of the Committee no less desirable, was the reservation of the term "brightness" as the name for the subjective sensory attribute correlated with the photometric quantity to which is now assigned the name "luminance."

The preliminary report also included a chart showing the correlation between a few physical, psychophysical, and psychical factors. In this diagram the concept, light, was placed in the psychophysical category, while the concept, color, was placed in the psychical category.

At the end of the report some tentative definitions of sensation terms were published which, at that time, were acceptable to slightly more than half of the Committee members, but the support for the definition of color as a sensation was not sufficiently enthusiastic to inspire confidence in that definition as the foundation of the report. The chairman and many members of the Committee felt that, while a compromise seemed to have been reached, no one was particularly pleased with the outcome.

Some time previous to the publication of the preliminary report, a suggestion had been made by a member of the Committee that possibly a more satisfactory basis could be established by defining color as a psychophysical concept. The records of the Committee's discussions do not establish with certainty the identity of this individual. This is of little importance since a similar suggestion had been made at least one hundred years earlier. For lack of a thorough search of the literature, an authoritative statement cannot be made as to the first appearance of such a suggestion, but the following quotation from Field's *Chromatography*,[11] published in 1835, is the earliest thus far found: "According to common apprehension, colours are inherent or substantial qualities of bodies, or material things. The more speculative have ascribed them to the sense of vision only, regarding them as intellectual* affections through the organs of sight; while a third class of inquirers has assigned them variously a medial stage between vision and colored objects; viz. in light."

The reaction of the Committee towards the psychophysical concept of color was at first quite unfavorable. However, the chairman requested a member of the Committee to prepare a set of definitions based on the psychophysical concept of color and these were circulated to all members (February, 1935). Again the reaction was not in the least enthusiastic, but a few had reached the point in their thinking where they felt that the psychophysical point of view

[10] L. A. Jones, J. Opt. Soc. Am. **27**, 207 (1937).

* A record of the votes on the various terms was published as a part of the preliminary report.

[11] George Field, *Chromatography or a Treatise on Colours and Pigments* (Chas. Tilt, London, 1835), p. 34.

* "Intellectual," as used by Field, probably was intended to convey the idea now more usually expressed by "mental" or perhaps even by "perceptual."

should be considered more seriously before it was finally rejected. A second manuscript was prepared explaining more fully the significance of the psychophysical definitions and discussing their merits. These notes were circulated to the Committee (February, 1936) with a letter from the chairman from which the following quotation is taken: "I should like to have every member read these with great care and to think seriously of the possible advantage of such a course. We should be very careful not to fall into a serious error simply because we have come to think in some particular way about this suggestion. I wish to stress the great importance of every member examining this proposal fairly and without prejudice." After careful consideration and lengthy discussions, some members of the Committee agreed that if an entirely consistent, logical, and usable system of color nomenclature could be evolved on a psychophysical basis, they would be willing to consider its adoption. This seems to have been the turning point in the evolution of the report.

Encouraged by this evidence of a disposition on the part of the Committee to give serious and unprejudiced consideration to the psychophysical concept of color, the chairman appealed to various members to assist him in the development and elaboration of such a scheme. While several contributed suggestions, the chairman is indebted most deeply to Elliot Q. Adams and David L. MacAdam for their assistance in preparing proposals based upon a purely psychophysical definition of color. These were submitted to the Committee for consideration in October, 1938. They were accompanied by a lengthy commentary setting forth the arguments for the adoption of such a point of view and by a discussion of the consequences of such a course.

It seems appropriate to review at this time some of the points brought out in this commentary. Almost universal usage, scientific as well as popular, indicates that light and color are concepts of the same kind and that it is inconsistent and irrational to place them in different categories. This inconsistency in the 1922 and 1937 reports might be eliminated in either of two ways: (1) *Light* might be transferred to the psychological category, or (2) *color* might be assigned to the psychophysical category. The first of these alternatives would require the abandonment of the psychophysical definition of light which has been quite generally accepted and used for many years. In 1930 the Standards and Nomenclature Committee of the Illuminating Engineering Society[12] published the following definition: "*Light:* For the purpose of illuminating engineering *light* is radiant energy evaluated in proportion to the luminous sensation produced by it." A modified form of this definition which reasserted the psychophysical nature of light was approved by the American Standards Association December 18, 1932 (ASA No. Z7-1932). (An equivalent definition was adopted in the 1941 report of the Illuminating Engineering Society[13] and later approved by the American Standards Association.) This definition of light as a psychophysical concept was apparently satisfactory to, and accepted by, Troland, who was recognized as an authority in the field of psychology as well as a physicist of the first rank. He says:[5d]

> "As we shall see (*cf.* page 71), the term, light, is no longer used technically as an equivalent of radiant energy, whether or not the latter is 'visible.' Light consists in radiant energy evaluated in terms of its capacity for evoking brilliance, when it acts upon an 'average normal' psychophysiological organism. Consequently, if we are interested to formulate psychophysical laws which have exclusively physical terms on one side of the equation, we must avoid the photometric concepts and use those of radiant energy, pure and simple."

On page 71, in accordance with the citation in the quotation just given, we find the following:

> "*Light as a Psychophysical Concept.*—Illuminating engineers have chosen to define light in terms of the photopic visibility function, because the latter characterized conditions of daylight vision. . . . It is evident that light, as thus conceived, is neither a physical nor a psychical quantity. It is rather a psychophysical notion, involving c.g.s. units, on the other hand, and a psychical dimension, which we may designate as ψ, on the other. Light can neither be identified with brilliance nor with radiant energy. It has the properties of both, taken together."

In view of this long established and accepted usage it seems useless to propose, even if it were

[12] "Illuminating Engineering Nomenclature and Photometric Standards," Trans. I. E. S. **25**, 728 (1930).

[13] "Illuminating Engineering Nomenclature and Photometric Standards," Illum. Eng. **36**, 813–852 (1941).

desirable, that light be assigned to the psychological category of concepts. So far as the chairman is aware, no member of this Committee has at any time indicated any dissatisfaction with the psychophysical definition of light, or has advocated its transfer to the psychological category. If the terms *light* and *color* are to be placed in the same group of concepts, there remains only the second alternative mentioned above, the transfer of color to the psychophysical category.

Considerable evidence is found in the literature to support the contention that, for the sake of logical classification, the two terms should be assigned to the same category.

Luckiesh[14] defines light as follows:

> "The term color in its general sense is really synonymous to the term light,"

and in common or everyday usage there is much evidence that many individuals instinctively think of the two concepts as being of the same type. Thus we find Addison (1672–1719) in commenting on the beauties of nature saying,

> "Among the several kinds of beauty the eye takes most delight in color. We nowhere meet a more pleasing or glorious show in nature, than what appears in the heavens at the rising and the setting of the sun, which is wholly made up of those different *stains of light*, that show themselves in clouds of a different situation." (Italics are ours.)

It is evident that the word "color" could be substituted for the expression "stains of light" without changing the meaning which the author intended to convey. The writer evidently considered the concepts of light and color to be extremely closely related and belonging to the same category of concepts.

While Parsons in his book on color vision[15] takes a rather extreme psychological point of view as to the nature of color, he evidently thinks of light and color as identical concepts and he says,

> "The psychological analysis of our sensations brings out other fundamental factors of importance. We not only see a light or a colour, but we see it at a definite time and in a definite place."

The form of the second sentence indicates clearly that Parsons considered light and color as concepts of the same category.

As a matter of record it should be mentioned that, during early discussions in the Committee, the suggestion was made that more than one definition of color might be formulated for use in this report, since there are at least four—and probably more—senses in which the term is used. (1) Color is sometimes used as a name for materials, such as dyes and pigments, but this Committee believes that the name "colorant" is preferable for use in this sense. (2) The spectral composition of radiant energy, and the spectral transmittance or reflectance of substances are sometimes referred to as color, but careful physicists will agree that color is an inappropriate name for these purely physical concepts. (3) The psychological concepts of color as a sensation or even a perception are very familiar and have been discussed in the foregoing pages. (4) Finally, the psychophysical concept of color, as a characteristic of light dependent on human vision is implied by extensive usage by laymen and scientists alike. The Committee decided definitely that only one definition should be given for the word color. All members agreed that the definition adopted should be adhered to (except possibly in direct quotations) throughout the report.

The most cogent arguments in favor of the psychophysical definition of color may now be summarized.

Light is generally recognized by usage and by definition as a psychophysical concept.

Color is intuitively classified in the same category of concepts as light and is so used by many.

Greater homogeneity in our classification of concepts is, therefore, attained by placing color in the psychophysical category rather than in the psychological.

The psychophysical point of view is the only one in harmony with the terms "colorimetry" and "colorimeter," as now used, and with the operations which are performed in the measurement and specification of color.

From a purely physical viewpoint, visual sensations and/or perceptions are as irrelevant as physical specifications are to a purely psychological approach. Whatever tolerance may be

[14] M. Luckiesh, *Color and Its Application* (D. Van Nostrand Company, New York, 1915).

[15] Sir John Herbert Parsons, *An Introduction to the Study of Colour Vision* (The University Press, Cambridge, 1924), p. 24.

given to various definitions of color in discussions exclusively physical or purely psychological in scope, the word should not be excluded by the terms of its definition from the subject matter in discussions where both physical and psychological aspects must be considered simultaneously.

The adoption of the psychophysical position not only admits but asserts that an evaluation of color has an inherently *medial* nature; implying at once an appraiser, the human observer, and an object of appraisal, radiant energy. This course seems to be amply justified on purely philosophical grounds, but, if less academic justification is desired, the purely practical considerations are fully sufficient.

We shall now return to the more or less chronological account of the evolution of this report to its present status. Following the distribution to the Committee in October, 1938 of the first draft of the detailed proposals for definitions based on the psychophysical concept of color, a meeting of the committee was held (October, 1938) at Niagara Falls. A very lengthy discussion indicated considerable dissatisfaction, but the general attitude toward this rather revolutionary change in the Committee's position seemed to be more favorable. Some members who were vigorous supporters of the psychological point of view agreed that in the following weeks and months they would give further consideration to the possibility of their accepting, in general, a psychophysical point of view and, furthermore, agreed to cooperate in an effort to eliminate some of the undesirable characteristics of the proposals as presented. In the year following this meeting little outward evidence of Committee activity was apparent, but, as a matter of fact, many members were thinking seriously about the possibilities of the psychophysical position and apparently were succeeding, at least to some extent, in adapting themselves to this new viewpoint.

The chairman wishes here to express his appreciation of the splendid spirit of cooperation and open-mindedness displayed by all members of the Committee during this transitional stage. It must be realized that many members were forced to go through a radical readjustment in their modes of thought on this subject in order to appreciate and fully evaluate the benefits to be derived from the adoption of the psychophysical viewpoint. During the latter part of 1938 and early 1939, the chairman received many communications from Committee members with valuable and constructive criticisms of the first drafts. These communications indicated a definite tendency toward a more favorable reaction to the psychophysical definition of color. While several members contributed valuable suggestions, the chairman feels he must acknowledge particularly those coming from Miss Nickerson, Dr. Gibson, and Dr. Judd. In fact, in October, 1939, Dr. Judd submitted a detailed outline in which color was placed in the psychophysical category. This outline suggested the correlations between physical, psychophysical, and psychological concepts, and in particular contained a valuable arrangement showing the position in the psychological category of the various modes of appearance of color and their attributes. This contribution by Dr. Judd was considered particularly significant since from the beginning he had expressed a decided preference for a purely perceptual (psychological) definition of color. Dr. Judd is to be highly commended for his willingness at all times to appraise without prejudice proposals at variance with his own views, and his willingness to meet more than half-way opinions of others in order to promote progress in the work of the Committee.

It should be mentioned also that during the evolution of the psychophysical treatment the old question of excluding the gray series from the category of colors was raised. No strong arguments in favor of such a course developed and the Committee is in favor of continuing to regard the black-white-gray series as colors.

During the latter part of 1939 and early 1940, Dr. MacAdam, with some assistance from the chairman, prepared revised drafts of the material which will constitute Chapters II (see the following paper) and VI of the report. In these, most of the criticisms and suggestions received from other members of the Committee were incorporated. In Chapter II the concepts relating to color are discussed in terms of a classification of the science of color into three categories: psychological, physical, and psychophysical. Chapter VI will present formal definitions of light and color as psychophysical concepts and the psycho-

physical aspects of color measurement were based upon these definitions. These drafts were sent to the Committee members shortly before a meeting held in New York in February, 1940. The general reaction at this meeting was decidedly in favor of writing the report on the basis of the psychophysical definition of color. In fact, the chairman felt that the approval was so nearly unanimous, although no formal vote was taken, that he was justified in proceeding as rapidly as possible with the completion of the report on this basis.

After this meeting the two chapters were again revised in accordance with suggestions from the members and they were resubmitted in the autumn of 1940. The next meeting of the Committee was held in February, 1941, at which time it was apparent that the Committee as a whole was satisfied with these two chapters in the form presented except for minor modifications which did not involve a change of the fundamental viewpoint. To facilitate final action on sections of the report as they were completed, a small group consisting of Dr. Judd, Dr. Hardy, and the chairman, was empowered to take final action of approval and such approval was given to Chapters II and VI. This cleared the way for the completion of other chapters. Until agreement was obtained on the subject matter of these two chapters, particularly Chapter II, it was impossible to proceed with the writing of other chapters since the definitions and principles set forth in these sections of the report control the fundamental character of the report as a whole and influence the statements and positions taken throughout the report.

At a meeting of the Optical Society in Cambridge, Massachusetts (February, 1941), the chairman presented to the Society a summary of the committee's activities and a detailed outline of the report. The Society was appraised of the Committee's decision to adopt the psychophysical definition of color. The definitions as formulated for the more important terms were discussed and the consequences of following the psychophysical scheme were explained. An abstract of this material was published in the Journal.[16] Members of the Optical Society were invited to submit comments and criticisms with respect to both the contents of the report and the basic principle on which it is based. Thus far no appreciable adverse criticism has been received.

The chairman is highly gratified with the results of the Committee's deliberations and particularly with the decision to adopt the psychophysical point of view. He believes he is correct in stating that the Committee as a whole shares this feeling. In the earlier stages of the discussion it appeared that a compromise between the physical and psychological points of view would be necessary. It now appears that the final solution, after all, is not a compromise but is the most rational position that can be taken in the definition of color and actually involves no surrender of principles either by psychologists or by physicists.

In concluding this introduction, the chairman wishes to express his deep appreciation of the assistance which has been given so generously by all members of the Committee. He is grateful for the willingness manifested at all times by them to consider proposals earnestly and without prejudice. The accomplishments thus far are directly attributable to this splendid spirit of cooperation.

[16] L. A. Jones, J. Opt. Soc. Am. **31**, 461A (1941).

Errata: The Development of the Microscope Objective

(J. Opt. Soc. Am. **33**, 123 (1943))

A. H. Bennett
Spencer Lens Company, Buffalo, N. Y.

On page 125, second column, line 14 from the bottom, reference mark 1 should follow the word "water," instead of appearing in the next line. In line 13 from the bottom for 1.24 read 1.05 and for 1.29 read 1.08.

The Concept of Color*

COLORS differ among themselves in three independent respects. Consequently, a threefold description is necessary and sufficient for the classification of colors. The three characteristics of color were first recognized subjectively, and consequently the ideas applicable to the description of color sensations are most familiar and furnish the most suggestive example of the triple system of classification. A color sensation is described when the hue, saturation, and brightness of the sensation are stated.† The hue can be described in terms of the familiar adjectives, red, green, blue, yellow, purple, and so forth. The description of saturation is not commonly undertaken beyond the use of rather vague terms, such as vivid, strong, and weak. The terms brilliant, pastel, pale, and deep, which are sometimes used as descriptive of saturation have connotations descriptive also of brightness. The description of a color sensation as bright or dim constitutes a statement of the brightness of the sensation. Brightness is the attribute** of color sensation which is most distinctly quantitative. This is a consequence of the fact that it is the attribute which varies most markedly when the magnitude of the stimulus is changed. The terms high brightness, medium brightness, and low brightness are appropriate for the description of the brightness of color sensation. Saturation also has a quantitative, as well as a qualitative character, and the use of the terms high saturation, medium saturation, and low saturation are suitable for the description of the saturation of color sensations. When, in a stimulus consisting of a combination of chromatic and achromatic light, the proportion of the chromatic component is increased, the saturation of the color sensation varies correspondingly. In the sense that it varies in the same manner as the proportion of the chromatic component in the stimulus, saturation may be considered a quantitative attribute of color sensation. Hue is rarely considered to be a quantitative attribute of color sensation.

* Chapter II of the forthcoming Colorimetry Report.
† See reference 3 of preceding paper.
** The noun "characteristic" may be read in place of "attribute" if such substitution will clarify the discussion for those who are not familiar with the psychological usage.

1. COLOR: CHARACTERISTICS OF LIGHT

Likewise, there are three characteristics of light in terms of which color may be specified. These are dominant wave-length, purity, and luminance. These characteristics of color correspond in a general way to the hue, saturation, and brightness attributes of color sensation. The attributes of color sensation and, also, the characteristics of color depend upon the phenomena of human vision, upon the kind of radiant energy and upon the rate at which it impinges on the retina. The radiant energy, which is the stimulus, may be specified by giving its spectral composition expressed in absolute units. The correlations between the spectral composition of the stimulus and the attributes of the resulting sensation are exceedingly complex. These correlations are greatly simplified when the intermediate psychophysical concepts are employed.

2. COLOR SENSATION: AN ELEMENT OF EXPERIENCE

Experience is so complex that the sensation of color is never experienced entirely apart from other elements of experience. These other elements of experience supplement and often modify, to some extent, the interpretations which we place on our sensations of color. Recognition and classification of objects according to the colors of the light they reflect is a most familiar process. In such recognition and classification, variations of many characteristics of objects, such as size, shape, gloss, texture, etc., are either ignored or discounted. Every experience is a unique event, the exact duplicate of which has never occurred in the past and can never recur in the future. Every analysis and classification of experiences involves the process of abstraction. Every classification necessarily discounts the uniqueness of each experience. Every abstraction stresses one feature of experience and subordinates or ignores all other features. In particular, visual perception is a variety of experience which can be analyzed into elements, the similarity or difference of which permits the classification and description of visual perceptions. The recognition of such elements is necessary for any classification and

study of actual experiences. The reality of these elements is frequently denied, because each is an abstraction never experienced apart from other elements. Such arguments usually conclude by attributing reality only to the whole unanalyzed experience. The intuitive recognition of elements of experience is, nevertheless, useful for orderly thinking, and doubt of their reality never interferes with their use.

3. MODES OF APPEARANCE

The following classification of modes of visual appearance is based on elements of visual perception. The attributes of the various modes of appearance are commonly considered to be descriptive of the *stimulus object*.

Shape and size are attributes possessed by all modes of visual appearance.

Transparency, varying from complete opacity to complete transparency, is an attribute possessed by all located modes of appearance.

In *located modes* of appearance the stimulus object appears to be within definite limits of distance from the observer.

Non-located modes of appearance lack the attribute of location.

The *aperture mode* of visual appearance is exhibited within the field aperture of photometers and colorimeters, and is the most common example of a non-located mode.

The *illumination mode* of appearance, which results from the awareness of the distribution of illumination in space, is classed as a located, but not as an object mode of visual appearance.

The *illuminant mode* of appearance of sources of light is a located mode.

The *object mode* of visual appearance is a located mode, which is further subdivided into:

Volume mode which has the attribute of *transparency* (excluding complete opacity), and

Surface mode which has the distinctive attribute of *glossiness*, as well as the attribute of less than perfect transparency.

These modes of visual appearance and their distinctive attributes can be recognized and classified independently of any classification of color. On the other hand, the recognition of color accompanies and supplements the recognition of modes of appearance. For instance, a glossy surface can be recognized as such if variations of color (primarily differences of luminance between highlights and surrounding areas) can be recognized in the light incident on the observer's retina from various portions of the observed object.

The distinction between color and the attributes by which modes of appearance are recognized and classified is emphasized in order to make clear the procedure which will be followed in this report, in which color is discussed apart from any discussion of the modes of appearance, which are perceived whenever the presence of color is perceived. Certain words, however, are associated with particular modes of appearance. For instance, the words "black" and "white" are commonly descriptive of *opaque* objects, although such usage is by no means exclusive. The use of these words for the description of aperture colors, of self-luminous sources, and of transparent materials, requires rather careful re-definitions which will not be attempted in this discussion.

Terms implying a dependence of color on some of the other attributes of visual appearance should be avoided. Thus, it is sometimes said that the color of one liquid is a transparent blue as distinguished from another whose color is said to be a murky blue. The same meaning can be conveyed just as clearly, without implying that transparent and murky are descriptive of the color, by stating that the first liquid is transparent and blue and that the second liquid is murky and blue. The usage recommended indicates that the descriptive terms for mode of appearance and color are mutually independent. The liquids may have a common color, describable as blue, although they differ in another characteristic, describable as transparent or murky, which is readily distinguished from the color characteristic.

Gloss is a characteristic which is readily distinguished from color, even though the comparison of the colors of surfaces which differ in gloss is frequently puzzling and difficult. Although they differ in appearance, air, water, and non-selectively absorbing mirror surfaces are not commonly considered to be different in color. It is rather uncommon to associate color with such

materials. The colors seen in or through such "colorless" materials are commonly associated with the objects seen by reflection or transmission.

The use of the names of materials for color names is frequently confusing because characteristics of the materials, other than color, are frequently suggested by such names. Gold, silver, and copper, are occasionally used as color names, but since the peculiar mode of appearance of metals is associated with these names, their use constitutes more than a color name, by suggesting also a familiar metallic luster. Like transparency, metallic luster is a characteristic of objects distinguishable from color, and names suggesting such characteristics should not be used as color names.

4. PSYCHOLOGICAL CONCEPTS

Sensation is the mode of mental functioning which is directly associated with stimulation of the organism.* It is specifically the direct result in consciousness of the present stimulation of the sense organs, as distinguished from *perception* which includes the combination of different sensations and the utilization of past experience in recognizing the objects and facts from which the present stimulation arises.

5. PSYCHOPHYSICAL CONCEPTS

Specifications of *stimuli* in terms of *equality*, or *differences*, of *sensations* experienced by human observers are called psychophysical measurements. The methods employed for the establishment of such measurement techniques, as well as the techniques themselves, are called psychophysical methods, and the concepts defined by the operations employed in these measurements are called psychophysical concepts. Although psychophysics is not limited to such methods and concepts, the discussion of psychophysics in this report will be limited to measurements based on equality and differences of sensations.

Since complex interactions between the responses of sense organs contribute to almost every sensation, there can be no assurance that a one-to-one correlation will exist between any sensation and the most nearly corresponding characteristic of the stimulus. Psychophysical methods of measuring such characteristics of stimuli give results that are related in a reasonable manner to the sensations experienced by representative observers under representative conditions of observation. In all branches of science, physics, chemistry, and physiology, as well as in psychophysics, standardization of the conditions of measurement is necessary for the establishment of any practically useful measurement technique and for the unambiguous definition of the quantities measured.[201]* Obviously, the quantities measured and the concepts defined by psychophysical measurements are not sensations.[202]

6. PHYSICAL AND PHYSIOLOGICAL CONCEPTS

For the sake of orderliness and clear thinking on the subject, it seems desirable to divide the subject of color vision into a few definite categories. Let us consider, therefore, the sequence of events which lead to the elicitation of visual sensation. Perhaps the schematic and somewhat fanciful diagram in Fig. 1 may be helpful in such a discussion. It may serve also to illustrate the

* Further refinement of the definition of sensation tends to reduce its content, until, finally, the concept is robbed of most of its customary meaning. As a result of such refinement of the concept, one school of modern psychology has arrived at the conclusion that it is useless to attempt to isolate pure sensation from the perceptual aspect of experience. For the purpose of clarity of exposition and appeal to the understanding of the readers for whom this report is intended, the unsophisticated concept of sensation described at the beginning of this section has been adopted. This concept does not imply any theory of the relation between sense organs and sensations, nor does it exclude the possibilities that simultaneous or successive responses of the same or different sense organs may interact without the observer being conscious of the interaction. Such interactions, which may be responsible for the phenomena of color constancy, adaptation, after-images, and contrast effects, would modify the sensations so that no invariant one-to-one correspondence could exist between stimulus and sensation. Adoption of common usage retains sensation as a meaningful concept. Several perceptions can have their origin in the same group of stimuli. The unpredictable and unclassifiable results of conscious judgment, which render each perception unique, are ignored in the process of analysis.

[201] P. W. Bridgman, *Logic of Modern Physics* (Macmillan, 1927).

* No attempt has been made to give extensive references in this chapter. Rather complete references will be given in later chapters when each of the subjects is discussed in more detail. The references cited here are considered of sufficiently general interest to justify their mention in this general introductory discussion.

[202] J. Guild, "Some problems of visual reception," *Discussion on Vision* (Cambridge, 1932), pp. 1–26.

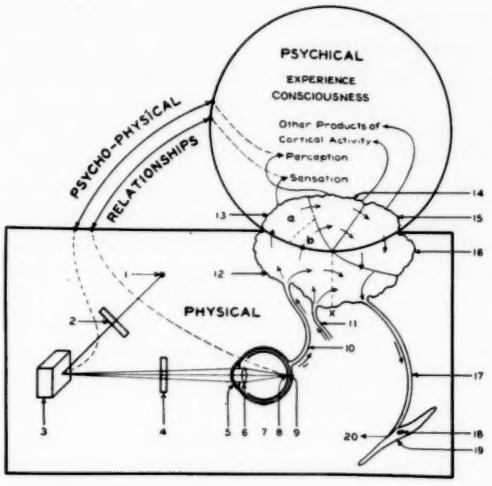

FIG. 1. Schematic diagram representing categories of visual psychophysics.

subdivision of our subject matter into three sections.

A radiator, 1, that is a "source of light" in common parlance emits radiant energy. *Radiant energy* is energy traveling through space in the form of electromagnetic waves of various lengths. As indicated in the diagram, this radiant energy, after being emitted by the radiator, is propagated through intervening space and falls upon an object, 3. Here some of the radiant energy is absorbed, some may be transmitted through the object, and some reflected. As indicated in the diagram, some of the reflected radiant energy is propagated through space and enters the eye, being refracted by various elements of the eye, 5 and 6, in such a way that an image of the object, 3, is formed on the retina, 7, at the point designated as 8.

The amount of radiant energy incident on the object is, of course, determined by the amount of radiant energy emitted by the source, by the distance between the source and the object, and by various aspects of the space through which it travels from the source to the object. The material occupying this space may be such that some of the radiant energy is absorbed or deflected so that it does not reach the object. In the schematic diagram, all of the absorption which occurs between source and object is represented as localized in the medium, 2. Modifications in the quality of the radiant energy may also occur as a result of selective absorption by the medium, 2.

The reflected radiant energy in traveling from the object, 3, to the eye where it enters the cornea, 5, of the eye, may also be modified both in intensity and in quality by the occurrence of absorption (including losses by scattering and reflection) by any materials in the intervening space, this absorption being indicated in the diagram as localized at 4.

When radiant energy falls upon the retina, 7, or, more specifically, upon the visual receptors, the rods and cones, which are component parts of the retina, a reaction of some type, probably photochemical or photoelectrical, occurs which results in the excitation of the sensitive receptors. This excitation gives rise to nerve impulses which are propagated from the rods and cones through the nerve fibers and synapses connecting these elements with the fibers of the optic nerve. Conduction of these nerve impulses then occurs along the fibers of the optic nerve, 10, which terminate in certain of the lower synaptic centers, specifically the external geniculate body in the cerebrum. Further conduction of the nerve impulses occurs through the synapses of the geniculate body into the sensory projection areas, 13, of the cerebral cortex. In the diagram the subcortical portion of the cerebrum is represented by the irregular area, 12, while the cortical areas of the cerebrum are designated as areas 13, 14, 15, and 16. The best evidence tends to indicate that no effect in consciousness is produced until the incoming nerve impulses reach the sensory projection area, 13, of the cortex. We may look upon the subcortical synaptic processes, 12, as "switching stations" controlling impulses flowing into the cortex and also, probably, to some extent, controlling efferent* nerve impulses of non-cortical origin which are responsible for certain motor reactions. Interactions between the nerve impulses from different portions of the retina appear to occur in these subcortical synaptic processes, 12, such inter-

* This word is common in the physiological and psychological literature and signifies conducting or passing outwards from the nerve centers to the muscles or glands. Similarly, *afferent* means conveying impulses from a peripheral part toward a nerve center, as the brain or spinal cord.

actions being responsible at least for certain phenomena of adaptation, such as a portion of color constancy, contrast effects, and perhaps after-images. Some efferent nerve impulses, 17, such as those activating the muscles, 19, for pupillary contraction, ciliary accommodation, and binocular convergence appear to be initiated in these subcortical synaptic centers, 12. Such muscular action, 20, is not ordinarily under conscious control. Thus, although nerve impulses originating in the association areas, 15, may act through the motor projection areas, 16, and initiate conscious control of the ciliary muscle and convergence, these functions are normally controlled directly by the subcortical synaptic processes, 12. Conscious control of accommodation and convergence seems to be accomplished through the interaction in the subcortical areas, 12, of efferent nerve impulses from the cortical areas, 15 and 16, with the afferent impulses from the optic nerve, 10. The efferent motor impulses resulting from such interaction proceed from the subcortical synaptic processes, 12, along the motor nerves to the end-plate processes, 18, located in the muscle fibers, 19, as a result of which muscular reactions, 20, are induced.

7. INTER-RELATIONS OF CONCEPTS RELATED TO COLOR

The arrival of sensory nerve impulses in the sensory projection area, 13, is generally considered to give rise to sensation. The further propagation of nerve impulses from the sensory projection areas into the association areas, 14, of the cortex may give rise to a more complicated psychical phenomenon termed perception. Perception is considered to arise not entirely from the immediate deliverance from one or more sense organs, but depends also to a great extent upon cortical activities arising from previous stimulation which we may conveniently refer to as stored memory records. According to this view, the character of a visual sensation is dependent entirely upon the nerve impulses arriving from the retina at a particular instant, while the more elaborate psychical phenomenon, perception, results from the possible contemporaneous deliverances of nerve impulses from one or more sense organs as interpreted in terms of previous experience, depending to a large extent, of course, upon the effects of previously received sensory impressions.

Further propagation of nervous impulses within the associational areas, 15, may produce a number of other psychical aspects of the mental life, such as thought, feeling, attention, imagination, association, emotion, etc. Continuing the cycle, nerve impulses arising in these areas of the cortex may be propagated into the motor projection area, 16, giving rise to efferent nerve impulses which are conducted along the motor nerves, 17, reaching the end-plate processes, 18, located in muscle fibers or the glands, 19, and thus resulting in an effect, 20, on the organism or its environment.

It is evident that everything which occurs from 1 to 8 is of a purely physical or objective nature. The characteristics of each link in the chain of events can be measured and specified completely in physical terms. Moreover, the interrelations between these various phenomena can be expressed as purely physical functions. We can, for instance, express precisely the characteristics of the image, 8, formed on the retina in terms of purely physical units. These characteristics, of course, include size, shape, and position of the retinal image, as well as the intensity and quality of the radiant energy at all points in the image.

It is convenient to refer to the entire chain of events leading up to the formation of and including the image on the retina as the *stimulus process*, in which the immediate stimulus is the *retinal image*, a pattern of radiant energy. The *response process* begins in or around the receptor cells, with the effect which occurs as a result of the absorption of the radiant energy of which the retinal image is composed, and continues inward along the afferent nerve fibers to the central nervous system and thence outward along the efferent nerve fibers terminating with the epithelial (that is either muscular or glandular) reaction and its effect on the organism or its environment. This entire chain of physiological events, 9 to 20, inclusive, will be called the *physical response arc*. The term physical is applied to the events from 9 to 20, as well as those from 1 to 8 because this entire chain of events, 1 to 20, appears to be causally connected and governed by objectively discoverable principles. Only the events from 1 to 8 can be in-

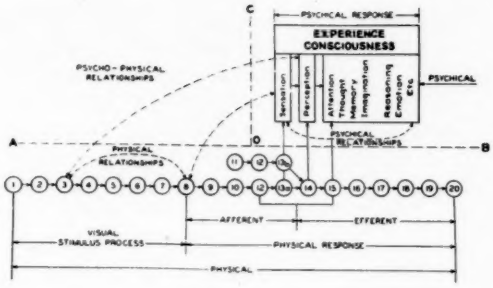

FIG. 2. Classification of concepts related to vision.

vestigated by the techniques employed in the specialized science of physics. The methods of physiology which are more appropriate to the investigation of the phenomena from 9 to 20 are adaptations of the methods of physics and chemistry to the study of living organisms, and the science of physiology can be grouped with the physical sciences in the same sense that chemistry is a physical science. Physiology and chemistry are not branches of the science of physics, but all three of these sciences are subdivisions of physical science. In the same sense, the physiological and chemical phenomena, 9 to 20, which are not proper subject matter for the specialized science of physics, are nevertheless physical in a generalized sense. In this sense, the phrase *physical response arc* is used to emphasize the connections between events 1 to 20, in contrast with the essential distinction of all of these concepts from psychical or subjective concepts. The physical response arc is divided quite naturally into two parts, namely, the afferent arc including conduction into the cerebrum, and the efferent arc, including conduction from the cerebrum along the efferent nerve fibers.

8. CONSCIOUSNESS: SUBJECTIVE ASPECT OF CORTICAL ACTIVITY

Since one effect of the arrival of visual sensory nerve impulses in certain regions of the cerebral cortex is a visual sensation, it seems reasonable to regard this sensation also as an aspect of the response to the stimulus. This response is of an entirely different nature from the nerve impulses themselves. Whereas the nerve impulses are the physical (specifically, physiological) aspects of the total response, the sensations are subjective, or psychical aspects of the response. Likewise, the resultant visual perception is also a psychical aspect of the response, although the character of the visual perception is not determined entirely by the immediate visual sensory nerve impulses, but is determined to a considerable extent by nervous activities in other cortical regions in which may exist physical records of previous sense organ stimulation and previous cortical activities. The subjective or psychical aspects of these latter elements may be regarded as the contributions of memory to perception. Other psychical phenomena, such as thought, feeling, imagination, etc., may also be regarded as psychical aspects of the response to the visual stimulus, although they are not dependent entirely upon the immediate deliverances of nerve impulses from sense organs.

In general, therefore, we may divide the aspects of the various phenomena thus far discussed into two very general categories, namely, physical and psychical. We have attempted to illustrate this division by placing in the lower rectangle all of the physical events, and in the circle above, all of the psychical phenomena. The fact that certain portions of the cerebral cortex, 13, 14, and 15, are shown in the area enclosed by the circle should not be taken to mean that the cortex itself, or the nervous activity within these cortical areas, is a psychical phenomenon. They are physical structures and functions, the psychical phenomena being the subjective aspect of these activities.

The sensory projection areas, 13, and the associational areas, 14 and 15, of the cerebral cortex have been placed within the circle designated as psychical merely to indicate the fact that the nervous activities within these areas are the direct or immediate determinants of consciousness. It seems to be the opinion of authorities in this field that no effect is produced in consciousness until the sensory nerve impulses reach the sensory projection areas and, moreover, that activities within the motor projection areas of the cerebral cortex have little, if any, direct representation in consciousness.

In Fig. 2 an attempt has been made to convey in a diagrammatic form approximately the same information as that presented in a more pictorial manner in Fig. 1. The diagrammatic form of

presentation has the advantage that pictorial or structural limitations need not complicate the presentation, and consistency can be attained with simplicity. The various physical factors involved in Fig. 1 are represented in Fig. 2 as small circles, inside of which is the same number as that applying to the corresponding event in Fig. 1. Everything below the horizontal line *AB* belongs properly in the general physical category.

The *visual stimulus* process as indicated extends from 1 to 8, while the *physical response* continues from 8 to 20, this response being subdivided into two parts, the *afferent* and the *efferent* response arcs. Since there may be doubt as to the exact boundary between these, the uncertainty is suggested by indicating that the afferent arc ends and the efferent begins certainly at some point between 12 and 15.

The psychical area lies above the horizontal line *AB* and to the right of the vertical line *OC*. In general it is indicated that the psychical aspect of the response to physical stimuli is experience and consciousness, these being made up of certain more specific psychical activities, such as sensation, perception, memory, etc.

It is perfectly possible to determine the relationship between any pair of items in the visual stimulus process. Likewise, it is conceivable that a relationship might be determined between any one of these items and any item within the physical response group or between any two items within that group, although, of course, it must be realized that the task of determining a relationship between an item within the stimulus process and one in the physical response process may be extremely difficult, at least in the present state of our knowledge and experimental technique. The diagram also indicates by its structure that nervous activity in the sensory projection areas of the cortex, 13a and 13b, gives rise to sensation. The propagation of nerve impulses from the sensory areas of the cortex into the adjacent associative area, 14, of the cortex and the interaction there with other possible cortical activities give rise to perception.

It is also possible to establish by suitable techniques, such as introspection, relationships between the psychical components of experience, these relationships being, of course, purely psychical relationships.

As indicated by the dotted lines extending from 3 and 8, in the physical realm, to sensation and perception, in the psychical area, relationships between various physical factors and various psychical factors may be established. These relationships obviously are neither physical nor psychical but are psychophysical relationships, as shown in Fig. 2.

On the basis of this classification of events we may therefore summarize by subdividing the relationships in which we are interested into three general classes: physical, psychophysical, and psychical. The *stimulus process* begins with the emission of radiant energy by a radiator and ends with the formation of an image on the visual receptors. The *physical response* begins with the reaction occurring in or around the receptor cells as a result of the absorption of radiant energy and continues through a series of neural processes which may culminate in a muscular or glandular action producing an effect on the organism or its environment. Traces of the physical response may remain in the nervous structure, and may exercise influences upon the responses to subsequent stimulation. The *psychical response* is the subjective aspect of the impulses in the sensory projection areas, and in the associational areas of the cortex.

Physical relationships describe the interactions of energy and matter, and are established by use of the physical criterion that they must be demonstrable independently of the sensory peculiarities and variabilities of observers. According to this criterion, two contradictory physical relationships or magnitudes cannot be tolerated. At least one of the two is wrong. The events represented by 1 to 8, inclusive, in Figs. 1 and 2, involve only interactions of energy and matter, and are clearly valid subjects for physical science. Contemporary physics is not actively engaged in the study of the events from 9 onwards, which involve the interaction of energy with living matter. The identification and measurement of the separate energy manifestations within the normally functioning living organism is beyond the capabilities of existing methods of physical investigation. This study of the interaction of energy with living matter is not being neglected, however. The foundations for this study are being established by the ingenious and skillful

investigations which constitute a thriving branch of the science of physiology.[203–207]

Psychological relationships include correlations between subjective aspects of the observer's response and are established by application of the criterion that the relationship must be evident introspectively or perceptually to the observer. Individual differences are accepted and, consequently, it is not to be expected that all observers will report the same psychological relationships. Disagreement is not always an indication of incorrectness of psychological concepts or relationships. Under some conditions group agreement may be expected.

9. PSYCHOPHYSICS

The third major subdivision into which the study of color will be classified, psychophysics, exists because there are important applications of relationships which can be discovered between physical stimuli and the sensory or perceptual aspects of the responses to these stimuli. For all practical purposes, psychophysical relationships are definitions, in physical terms, of concepts derived from the subjective aspects of the response of the human organism to physical stimuli. The criterion of subjective significance governs the relationships on which the definitions are based. Since this use of the introspective criterion introduces all of the variabilities and peculiarities of individual observers into psychophysical relationships, these relationships are, strictly speaking, variable, dependent on the observer and not universally verifiable. The usefulness of concepts and relationships based on average values of the psychophysical relationships for many observers has led to the inclusion of these averaged and standardized relationships in the category of psychophysics. Some authors, who ignore the human significance of these data in order to create an illusory simplicity for the purposes of engineering, look upon the concepts defined by these standardized relationships as purely physical because the fact of standardization has been substituted for the criterion of subjective reasonableness. Some authors regard luminance, for instance, as a derived physical quantity, since it can be computed from the spectro-radiometric data of the emitting surface by use of the standard psychophysical data without the necessity for any visual observation or measurement.[208] Such a point of view is quite misleading and inadequate for the discussion of color. The concepts, such as luminance, which are defined by the standardized psychophysical relationships, are classed as psychophysical in this report.

In the schematic diagram (Fig. 1) the position of the psychophysical field is shown as lying between that of the physical and psychical, and, as indicated by the dotted lines, some selected psychical aspect of the response may be correlated with a selected element of the stimulus process through the instrumentality of the psychophysical relationship. Since relationships of this type are of such fundamental importance in the solution of color problems, it seems desirable for the sake of emphasis and illustration to cite a specific example of one such psychophysical relationship. We know that the radiant energy coming to us from the sun is composite in character, consisting of a mixture of radiant energies of many different wave-lengths or frequencies. By using a suitable dispersing system, this radiant energy can be separated into its component parts. Now we can take a given amount of some particular frequency and find how much of another frequency is required to produce a "brightness" (sensation) equal to that produced by the first sample. By continuing this process until all frequencies which are capable of stimulating the eye have been compared with the first sample or standard, we may determine how efficient radiant energies of the various frequencies are for the production of "brightness." This efficiency we may term the *luminous efficiency* meaning that it is a numerical expression of the quantity of light corresponding to a given sample of radiant energy. It is evident that this luminous efficiency is a quantity that is neither purely physical nor purely psychical, but is a relationship between the psychical and physical

[203] Ivan P. Pavlov, *Lectures on Conditioned Reflexes* (International Publishers, New York, 1928).
[204] E. D. Adrian, *The Mechanism of Nervous Action* (University of Pennsylvania Press, Philadelphia, 1932).
[205] C. Sherrington, *The Integrative Action of the Nervous System* (Yale University Press, New Haven, 1920).
[206] S. R. Detwiler, J. Opt. Soc. Am. **30**, 42–50 (1940).
[207] H. K. Hartline, J. Opt. Soc. Am. **30**, 239–247 (1940).
[208] Parry Moon, *Scientific Basis of Illuminating Engineering* (McGraw-Hill, New York, 1936), pp. 544–545.

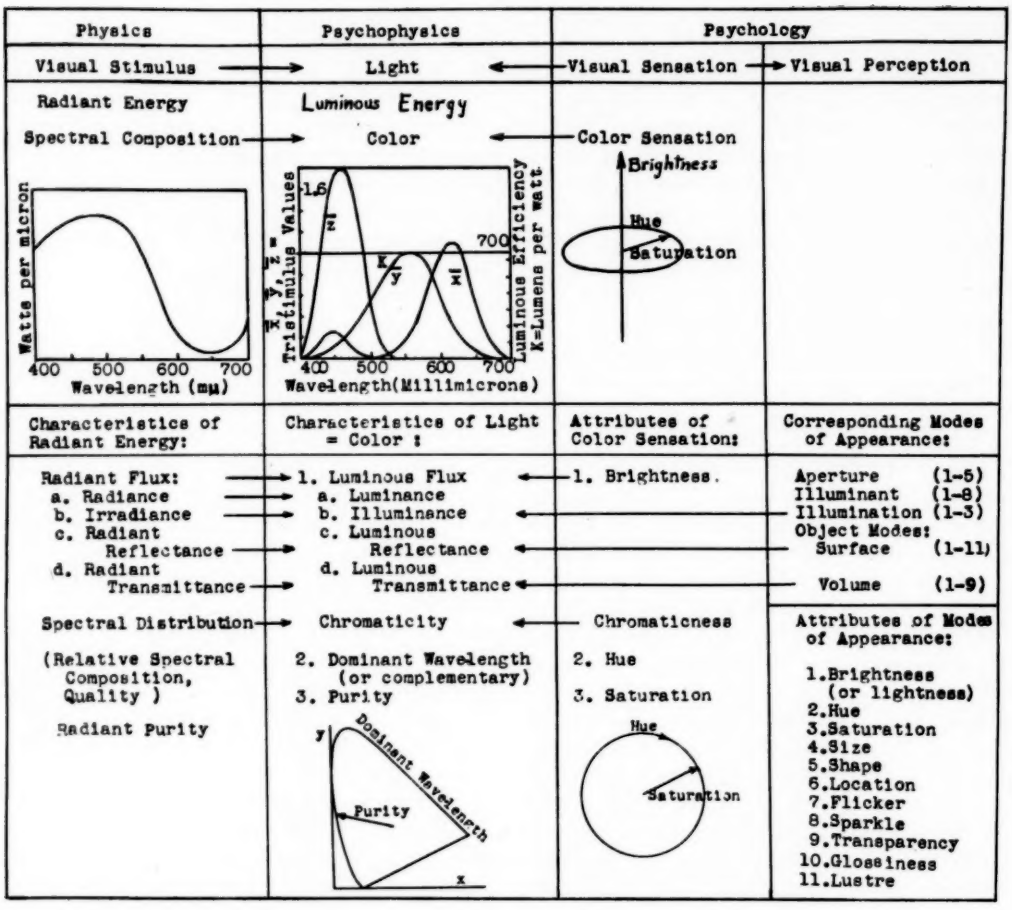

FIG. 3. Correspondence between attributes of radiant energy, light, visual sensation and perception.

aspects of radiant energy. We say, therefore, that *luminous efficiency* is a *psychophysical term* or *quantity*. As we shall see later, the particular relationship which expresses the dependence of luminous efficiency on the frequency of radiant energy is a particularly important one in the solution of many color problems. It will be discussed at greater length in the section devoted to psychophysical relationships.

10. CLASSIFICATION OF CONCEPTS RELATED TO COLOR

We feel that the discussion given in the preceding paragraphs has established the reasonableness of our proposal to subdivide the subject matter with which we must deal in the study of color into the following sections:

1. Psychological concepts and relationships.
2. Physical concepts and relationships.
3. Psychophysical concepts and relationships.

Therefore, we may proceed to classify the more important concepts with which the discussion of color is concerned under the headings of the names of the sciences, physics, psychology, and psychophysics as is illustrated in Fig. 3. To some extent the concepts named at corresponding positions in the several columns are closely related, but in some cases, such as in the listing of the modes of appearance and the attributes of these modes, the parallelism of the columns has

been abandoned in order to exhibit the dependence of the appropriate photometric quantity on the mode of appearance. The concepts included under the category of psychology have been divided, for convenience, into sensory and perceptual classes. The division greatly aids in the clarification of the relations between the physical and psychological phenomena, which are the subject matter of the science of psychophysics. The co-ordinated contributions of the sciences of physics and psychology to the science of psychophysics are indicated by the arrows at the heads of the columns. The contributions of the sensory elements of experience to the more highly elaborated experiences classed as perceptions are also indicated by an arrow from the term visual sensation toward the consequence, visual perception.

The evaluation of radiant energy in terms of its capacity to produce brightness has already been discussed. This evaluation of the spectro-radiometric curve (shown in the physical column) is accomplished by use of the luminous efficiency function which is represented by the curve labeled K in the psychophysical column. The resultant quantity is called the quantity of light* or luminous energy. Luminous flux is the rate of flow of luminous energy. The luminous flux incident on a definite area of the retina corresponds to the brightness attribute of visual sensation. The quantities, luminance, illuminance, luminous reflectance, and luminous transmittance are similarly evaluated in terms of luminous flux by use of the luminosity function, K. These several different alternative manners of expressing the quantitative characteristics of light are used in the appropriate situations described opposite them in the column of the perceptual concepts. The parentheses following the names of the modes of appearance indicate the attributes which each mode may exhibit. The code used in these parentheses is given under the heading "Attributes of modes of visual perception." Only three of these attributes correspond closely to concepts included under the other categories. The other seven attributes are usually perceived by human observers because of the spatial and temporal characteristics of visual stimuli.

* See reference 13 of preceding paper.

The characteristics of light which are specified by dominant wave-length and purity may also be specified by the location of a point in the chromaticity diagram shown at the bottom of the psychophysical column. Chromaticity includes both of these characteristics, and corresponds to the concept of relative spectral composition or quality of radiant energy, and to the chromaticness* of visual sensation. The circular diagram at the bottom of the psychological column indicates the type of classification which is suitable for the description of the chromaticness of color sensations. Since, when a complete series of hues is arranged in a subjectively reasonable sequence, the first member of the series always very closely resembles the last member, the hues are reasonably arranged in a closed curve, of which the circle is the simplest and most commonly adopted form. Similarly, when the saturations of all hues are decreased, the sensations all approach a common residual or neutral which may be represented by a point somewhere within the closed hue circuit. For simplicity this neutral or achromatic sensation is represented by the center of the hue circle and various saturations of any one hue are represented by points along a radius of the circle. Increasing distance from the center signifies increasing saturation. The general classification of color sensations requires the addition of a third dimension for the representation of the brightness attribute, in the manner indicated at the top of the column labelled color sensation. The three distribution functions represented at the top of the psychophysical column are the basis for the internationally standardized method of evaluating color in terms of equivalent stimuli, consisting of the combination of three standard stimuli. The intensities of the three standard components in the stimulus equivalent to any

* Chromaticness is a new term, suggested here for the first time, which is purely tentative and designed to fill a gap in the naming of corresponding psychophysical and psychological terms. That the need is real is indicated by the prevalent indiscriminate use of the term chromaticity in both the psychological and the psychophysical senses. Chromaticness is subject to change in favor of any name agreed upon by psychologists for exclusive use in the subjective sense, corresponding to the psychophysical concept of chromaticity. The ending "-ness," which conveys some idea of magnitude is no more objectionable in this term than in whiteness, glossiness, and even brightness, which require statements of "what kind" as well as "how much" for complete descriptions.

color can be determined as the totals of the spectro-radiometric data of the sample weighted by each of the distribution functions shown. Color may be specified by the "tri-stimulus values," which result from the calculations just described. The proportions of two of the tristimulus values in the total of the three are represented by the coordinates of the point representing the color in the chromaticity diagram. The dominant wave-length and purity of the color are simply and directly related to the location of the point in the chromaticity diagram. The hue and saturation attributes of color sensation and perception correspond to the psychophysical characteristics of color: dominant wavelength and purity. The scale of values shown on the right-hand side of the diagram representing the standard distribution functions indicates that the curve representing the luminous efficiency of radiant energy of various wave-lengths is identical in shape with one of the standard tristimulus distribution functions. The corresponding tristimulus value of any color is directly proportional to the photometric intensity of the light, and this value is used as the specification of color which corresponds most directly with the brightness attribute of color sensation.

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New Precision Instrument for Measuring Gloss

THE new Aminco-Scott Glossmeter (goniophotometer) measures high, medium, and low gloss (from zero to 100 percent) of plane surfaces of materials over $2\frac{1}{8}\times 3$ inches in size, such as paint finishes, enamels, lacquers, metals, wood, paper, plastics, glass, etc. Results are in terms of the I.C.I. Normal Observer and I.C.I. Illuminant *C*.

The kinds of gloss (relative apparent reflectance) measured with this instrument are specular gloss, contrast gloss, distinctness-of-image gloss, absence-of-bloom gloss, and many other optical properties of surfaces of all kinds. It is especially useful for A.S.T.M. method D523 for measuring specular gloss of paint finishes.

Some suggested supplementary uses are the measurement of the hiding power of deposited finishes, cleansing power of soaps and detergents, relative apparent reflectance of plane surfaces for obtaining Munsell value, index of refraction, resistance of surfaces to abrasion, weathering, wear, etc., and for the measurement of glare.

Illumination is adjustable from minus 30 degrees to plus 70 degrees from the normal. The receptor is adjustable from plus 30 degrees to minus 70 degrees from the normal.

Angles may be read to 1 minute of arc.

Measurements of relative apparent reflectance from zero to 100 percent (in steps of 0.01 percent) can be made.

Measurements can be made rapidly. For example, a complete gloss curve of a high gloss sample can be obtained in approximately thirty minutes.

The instrument has sufficient sensitivity and wide range to measure relative apparent reflectance from high gloss to flat gloss without the use of neutral filters, wedges, or similar devices which are difficult to reproduce or calibrate.

The instrument operates on 110–120 volts 60 cycles (controlled frequency) single-phase a.c., and is unaffected by fluctuations in line voltage. It need not be operated in a darkened room. There is no upkeep cost except infrequent renewal of the lamp.

The Aminco-Scott Glossmeter consists essentially of four main components: (1) goniophotometer; (2) reference plate and sample holder; (3) control and measuring unit; (4) galvanometer. A standard glass reference plate is supplied.

The entire outfit weighs approximately 55 lb.

Complete description and specimen curves are given in Bulletin DC2115, which is available from the manufacturer, the AMERICAN INSTRUMENT COMPANY, *Silver Spring, Maryland.*

Some Factors and Implications of Color Constancy*

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I. PROBLEMS OF COLOR CONSTANCY

THAT colors and forms tend within limits to remain constant in spite of changes in illumination and orientation is well-known from common experience. It was recognized by both Hering and Helmholtz who saw in it problems for visual science and formulated explanations to account for questions it raised. According to Helmholtz[11] we learn to judge how objects should look in white illumination and see them accordingly under different lighting conditions. While we are not conscious of the basis of our inferences learning operates to restore colors as they should be in daylight. Helmholtz emphasized the fact that colors interest us mainly as properties of objects and not in their own right. Hence the approximate constancy. Hering put it thus: "Approximate constancy of the color of objects in spite of large qualitative and quantitative changes in general illumination of the visual field is one of the most striking and important facts in the domain of physiological optics. Without this approximate constancy a piece of chalk on an overcast day would appear as dark as a piece of coal on a sunny day and in the course of one day would take on all possible lightnesses between white and black."[15] Whereas Helmholtz attributed constancy to learning and judgment, Hering sought more tangible physiological mechanisms as the cause such as pupillary changes, adaptation, and contrast. But Hering felt obliged to invoke psychological factors in addition because he believed that "All the things which are known to us from past experience . . . in respect to color are seen through the spectacle of 'memory colors.'" Katz at first[21] accepted the Hering concept of memory color but later[22] in the second edition of his book admitted that the evidence against was greater than the evidence for memory color.

It is now seen that the problem of color constancy involves not one but many aspects of color vision as well as the spatial functions of the eye. Among the questions to be clarified before the problems of constancy can be satisfactorily explained the following seem most important: (1) Conditions and modes of colors; (2) Dimensions of colors in the various modes; (3) Tolerance to changes in amount and composition of the illumination: (4) Relations of contrast, constancy, adaptation, assimilation, and other visual processes; (5) Effects of neighboring colors, surroundings, distance, and special conditions of vision such as tubular and lens vision; (6) Spatial effects on colors and effects of color on spatial attributes of vision; and (7) Role of retinal *versus* central mechanisms. The problems of color constancy are thus seen to be neither simple nor univocal.

II. CONDITIONS AND CHARACTERISTICS OF FILM AND SURFACE COLORS

We are indebted to David Katz for bringing the problems of constancy into the laboratory and for devising a way by which they can be controlled and measured. Katz used several methods for investigating constancy, the most striking being the cast shadow set-up as shown in Fig. 1. Two color mixers are placed before a homogeneous background and a screen is placed between them. Light coming from one side fully illumines one mixer and is partly cut off from the other. An observer is asked to obtain a match between various mixtures of white and black on the shadowed side and the fully illuminated mixer. Starting with 360^{b} W on the shadowed mixer it is found that although 360° W on the illuminated side is too light for a match the disk mixture which does match is not as dark as would be expected from the reduction in illumination on the shadowed side. After a match is obtained if the two disks are viewed through small holes in a neutral screen placed before the observer it is found that the shadowed disk is much darker than the illuminated one. If the two disks are again matched as "hole" or aperture colors they will not be equal in unrestricted

* Paper presented at the Symposium on Vision at the Optical Society Meeting in New York City, March 5–6, 1943.

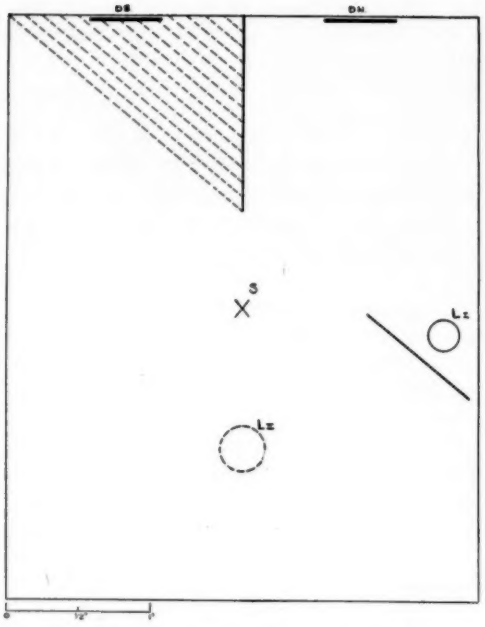

FIG. 1. Conditions for investigation of lightness constancy. Light source L_I illuminates the normal color mixer *DN* and casts a shadow by means of a screen on shadowed mixer *DS*. The observer sits at *S*. L_{II} is an optional room light.

vision. Matches made under the one set of conditions do not hold for the other. A photograph of the disks when matched in free observation shows the shadowed disk as too dark or as if the camera sees the disks in aperture vision. Anything done to narrow the field of view to the disks themselves tends toward the aperture appearance: squinting, monocular vision, small visual angle, and "analytical attitude." Peripheral vision also tends to approximate aperture viewing.

The changes in lightness just described as one views colors in free and in aperture conditions are not the only effects observable. Whereas the two disks match very well as aperture colors, in free observation observers find it hard to obtain equality between all characteristics of the colors simultaneously: when the disks are equal in one respect they still appear different in others. At this point it should be noted that while the term constancy has been extensively used in the literature, nothing like complete preservation of all color dimensions is found under changing conditions. At best only one or two dimensions remain stable while others change. Recognition of this fact led Katz to postulate additional dimensions for the achromatic series which can no longer be regarded as uni-dimensional. The other changes which follow change in what Katz called "mode of color appearance" concern aspects of color which are not usually regarded as pure color qualities. Aperture colors lack surface texture and tend toward a common soft, filmy appearance. They have no definite localization behind the aperture in which they are seen but do tend to stay in the frontal-parallel plane with respect to the observer. Colors in free observation are characterized by surface texture or "microstructure," are hard and resist the gaze, and take whatever plane the object is in since they belong to objects. Surface colors approximate various degrees of constancy while aperture colors tend to maintain closer correspondence with the actual stimulus impinging on the retina. We now know that aperture colors are no less subject to influence from the aperture screen than surface colors are to their surroundings.

Still other modes and their conditions were described by Katz: volume or bulky colors, transparent surface and transparent film colors, mirrored, glossy, and lustrous modes. Different modes may require different descriptive terms or dimensions. All modes of appearance may be reduced to the film mode by viewing the color through the reduction screen technique described above. This mode Katz regarded as the most primitive in color vision. The Viennese group under the leadership of Bühler has identified the film mode with rod function and the surface mode with cone action. It does not appear that sharply defined mechanisms are necessary for the various modes of color which Katz has described.

III. ROLE OF THE ILLUMINANT

It is natural that in the first accounts of constancy the role of the illumination should have been singled out for attention since the problem first arose in connection with preservation of object color in spite of change in illumination. Accordingly Katz[21] ascribed color constancy in chromatic illumination to "noticing" the abnormal lighting so that object colors are trans-

formed back to their "normal" appearance. Jaensch[16] asserted, on the contrary, that transformation occurs because object color is abstracted from illumination or at least the illumination is not noticed. Bühler,[4] followed by his students, Bocksch,[2] Krauss,[27] Kardos[19] and others, stressed the differences between rod and cone functioning and separation of general illumination from object color by means of stray light from dust particles in the air and in the media of the eye. Thouless,[37] interested in the constancy of form, points out that perception gives neither perfect constancy nor one-to-one correspondence with stimulus variables, but rather presents us with a compromise between the two which represents a regression toward the real.

Psychological terms like noticing or discounting the changes in illumination, transformation, and regression toward the real, imply some standard set of conditions in which object colors were seen and toward which they tend to revert under new conditions. Several findings indicate that, while the net effect may be constancy in many cases, these expressions give no indication of the mechanisms by which the result is achieved and may give a wrong steer to thinking. Thus when observers are asked to report on colors in deep shadow or in strongly chromatic illumination they do so without knowledge of what the "normal" colors should be and without reference to external standards if none is provided. On the other hand, even if observers are made fully aware of the nature of the illumination conditions and how they differ from so-called normal, knowledge does not affect the striking phenomena previously reported.[13] Finally, experiments with animals preclude the possibility that higher psychological functions are involved in the phenomena of constancy unless we are willing to grant much more to infra-human organisms "mentally" than is possible on many other grounds. Animals below man show tendencies toward constancy as strong as he. Thus Köhler[25] found that chimpanzees chose food from containers of high (low) reflectance after the illumination was changed so that the absolute amount of light was less (more) than from food boxes nearby of low (high) reflectance. Locke[29] reports that humans showed degrees of approach to constancy ranging from 0.10 to 0.23 (1.00 representing perfect constancy) whereas rhesus monkeys had values ranging from 0.47 to 0.65. Katz and Révész[23] trained hens to discriminate rice grains which were white in daylight from grains colored yellow and found that the hens subsequently continued to pick the "white" grains in strongly yellow illumination. Burkamp[5] testing fishes (Cyprinides) found strong tendencies toward both lightness and chromatic constancy with changes in amount and quality of illumination.

With this evidence from animals below man it does not seem necessary to postulate higher cortical activity to explain the facts of color constancy. The concept of "normal illumination" is one of the concepts implying that constancy springs from more or less complicated learning mechanisms and it has therefore been subjected to criticism. There are some senses in which it may be legitimate to speak of "normal" illumination even though it may be misleading in other respects. Katz suggested[21] that details of surface structure are best seen in normal illumination and from these details texture and other object properties are identified. This criterion depends upon the resolving power of the eye which is usually regarded as a spatial function rather than a color function, although resolution is known to be affected by wave-length as we shall see below. Judd and the writer[17] attempted to synthesize an illuminant in which it was believed all non-selective samples would appear achromatic. This criterion of normal illumination is based on chromatic properties of the illuminant. Preliminary attempts at synthesis were not successful but the possibility is not thereby ruled out that such an illuminant may be found. If achromaticity of non-selective samples of all reflectances proves to be too stringent a requirement for normal illumination, Illuminant *C* of the I.C.I. might be referred to as normal and the colors seen under it might be taken as the normal colors of objects. But this raises the difficulty that what is normal for one purpose may not be for another, hence relevancy to purpose at hand may be the deciding factor in the choice of a normal illuminant. If this is true then there may be more than one normal illuminant.

While the concept of normal illumination has been subjected to criticism and has undergone

revision as a result, it has served to focus attention on the role of the illumination as one of the general conditions of vision. The part played by the illumination will be further discussed in succeeding sections.

IV. TOLERANCE FOR CHANGES IN ILLUMINATION AND IN THE DIMENSIONS OF COLORS

We have just seen that animals far below man compensate for changes in amount and composition of illumination by responding to objects as if their colors retained their daylight appearance. Does this mean that changes in general illumination pass unnoticed as Jaensch asserted or is there some means by which object color is distinguished from the illumination in which it appears? Perception of illumination is, as Katz has insisted, as immediate as awareness of object color and in many cases the composition of the illuminant must be exactly right for matching and grading objects. We come here to the limits of compensation which have important consequences which we must now discuss.

Reverting to the cast-shadow experiment we find that two white disks in different illuminations may be equated for lightness but the one in shadow is seen as "white-in-dim-illumination," that is, as a less pronounced white. Were the two disks alike in every respect it would mean that we cannot distinguish between bright and dim illuminations. The failure in this case to achieve complete constancy serves as a cue to the fact that the illuminations are different. Similarly decrease in illumination makes red and yellow less pronounced as chromas while green and blue become more pronounced (Sinemus[35]). Increase in amount of illumination causes opposite effects on pronouncedness of these hues. Sinemus has found that artificial production of micropsia through the use of concave lenses has the same effect as increase in illumination on the pronouncedness of colors.[35] White and black also behave differently in high and low illuminations and in micropsia, the former gaining in pronouncedness in strong light, the latter losing under the same conditions. Pronouncedness thus furnishes a direct clue to conditions of illumination in the case of both chromatic and achromatic colors.

When the composition of the illumination is changed radically from daylight, as in spectrally homogeneous illuminants, the usual relations between the fundamental dimensions of color are greatly altered. Thus highly reflecting samples in spectrally homogeneous illumination cannot be matched by any mixture of daylight colors because the former are both lighter and more saturated than any possible daylight colors (Helson and Jeffers;[13] Krauss[27]). From experience with daylight colors it seems like a contradiction in terms to assert that colors can be both whiter and redder at the same time since increase in the one means decrease in the other under "normal" viewing. Breakdown in constancy also occurs when objects are viewed at a distance and the results are quite surprising, as Schmeckebeier[34] has described them. Thus yellow appears red, then orange, and lastly yellow with decreasing distance; violet appears blue, then brown, then black, and lastly violet. Once the limits of compensation have been reached color changes from common experience are many and at first sight baffling.

The differential responses to complex viewing situations are largely responsible for whatever constancy exists and help explain other facts as well, once it is recognized that the visual mechanism behaves as if it had different sensitivities for different dimensions. The eye is least sensitive to change in general illumination. Krüger[28] found that thresholds for general changes are 2.2–5.0 times greater than thresholds for lightness of grays on Maxwell disks. The same fact is noted by Marzynski[31] who distinguishes between partial and total changes in the visual field, the latter having less effect on lightness than the former. Gates[7] found the "qualitative" limen (for lightness?) to be about 12 percent higher than the limen for "intensitive" changes (for brightness?) using Maxwell disks, a fact confirmed by Henneman.[14] Approaching the matter from a somewhat different angle, Miss Martha DeWitt at Bryn Mawr College determined the range of reflectances of non-selective samples on non-selective backgrounds which were called white, gray, and black, by more or less naïve observers. Table I shows that a wide range of reflectances can yield black, gray, or white, depending upon reflectance of background (cf. Judd[18]).

In this section we have distinguished three

differential responses of the visual mechanism: (1) to changes in general illumination; (2) to white-gray-black quality; and (3) to bright-dim quality of either objects or illumination. These three discriminatory responses enable the eyes to perform multiple functions simultaneously: to apprehend the general level and quality of illumination, and to distinguish between objects and their surroundings. These functions include chromatic as well as achromatic qualities. Because we have spoken of different discriminatory responses with different thesholds of response it should not be inferred that we therefore regard the visual mechanism as composed of several mechanisms. Rather, we regard the visual apparatus as a unitary mechanism with extraordinary lability in function. Re-interpretation of such terms as adaptation, contrast, assimilation, and induction makes possible a unitary view of how the eyes can perform these multiple functions. Already highly successful physiological theories have been elaborated by Hecht and his coworkers[9] and mathematical theories by Judd[17] and Spencer[36] have resulted in successful predictions of color conversions. The known properties of such retinal substances as visual purple and similar properties of bleaching and regeneration which other retinal pigments undoubtedly possess[10] make such terms as adaptation, contrast, and assimilation more than descriptive of color phenomena for they apply to the underlying physiological processes at the basis of vision as well. In the remainder of this paper the attempt will be made to show how these processes can be made to explain the chief facts of constancy* and related phenomena by means of a single theory.

TABLE I. Reflectances of non-selective samples on non-selective grounds found to appear black, gray, and white.

Background reflectance	Lightness quality		
	Black	Gray	White
0.037	0.037	0.037–0.377	0.377–0.803
0.230	0.037–0.042	0.042–0.430	0.430–0.803
0.803	0.037–0.084	0.084–0.630	0.630–0.803

* In the remainder of this paper the term "constancy" will be used as little as possible and the term "compensation" will be used instead. The change in terms is desirable because constancy is only approximate and never applies to all the dimensions of color, even when perfect. The term compensation implies that the visual mechanism compensates for changes in conditions of viewing up to certain limits beyond which approximations to constancy are absent. According to the terminology employed by the writer, when the limits of compensation have been reached colors change and "color conversion" is said to have occurred. Discussion of color conversion will be found in previous publications by the writer (references 12, 13).

V. EFFECTS OF BRIGHTNESS OF STIMULUS, REFLECTANCE OF BACKGROUND, AND DEPTH OF SHADOW ON LIGHTNESS COMPENSATION

I propose now to discuss some experiments on lightness constancy carried on by Mr. R. W. Bornemeier at Bryn Mawr College, which were designed to determine whether our theory would account for certain experimental results reported in the literature. The bearing of these experiments on some of the striking cases of constancy will be stressed.

Using an experimental situation similar to the cast-shadow set-up of Katz (Fig. 1), observers were required to match a black-white Maxwell disk in bright illumination with one in shadow for various mixtures of the latter. The reduction screen technique of Katz was unnecessary since we could measure the luminances of the disks with a Macbeth illuminometer. Instead of using any of the formulae for constancy couched in terms of degrees white of disks in free and reduced observation we have used the ratio of luminances in apparent footcandles of the two disks as measures of compensation. The larger this ratio is the greater the compensation since the eye has had to compensate for greater differences in illumination. While the main variable of interest to us was reflectance of background, since this factor has either been overlooked or too casually dismissed, reflectance of shadowed disk, and depth of shadow were also investigated. The interrelations of these three variables seemed to us to be of paramount importance in the explanation of phenomena of visual compensation.

Turning first to effect of reflectance of the shadowed disk we note that as reflectance changes from 0.80 to 0.03 the color of the disk changes from white to gray and finally becomes black. Hence three compensations are involved as reflectance of disk is lowered: with high reflectances the compensation consists in a lightening of the shadowed disk while with low reflectances the effect consists of a darkening of the

brightly illuminated disk. In Table II it is seen that the apparent footcandle ratios increase with decreasing reflectance of shadowed disk, except for the white background where there is an increase, then a decrease, and then a sudden increase again. Greatest luminance ratios are found with lowest reflectance or black disk where we find that with deepest shadow the ratio of luminances is 3766 to 1, an enormous difference for two disks said to be equally black! It appears that black endures more light while remaining black than white endures shadow while remaining white as a comparison of ratios for white and black shows in Table II. Since the maximum and minimum ratios are found with black and white respectively, the intermediate values for the grays show that they stand between white and black in degree of compensation.

Reflectance of background which had been previously found to be of decisive importance in determining hue, lightness, and saturation of samples in chromatic illuminations[12] is of equal importance for the achromatic colors in "white" light. As shown by Fig. 2, highest degrees of compensation are found with white background and least with black background, gray background occupying an intermediate position. The use of backgrounds of different reflectances demonstrates that visual compensation is not an unilateral effect springing only from the so-called "abnormal" illumination. Compensation is just as much darkening of surfaces of low reflectances in high illuminances as it is lightening of surfaces of high reflectance in low illuminances although the latter has received more acclaim. The most striking effects of background are found when a divided background is used, white on one side and black on the other. Using illuminances having a ratio of 18 : 1 observations were made with white background on illuminated side and black background on shadowed side and then with these backgrounds interchanged. The results are startling and help to explain some of the paradoxes in the literature without recourse to psychological processes as such. The plot of the luminance ratios as a function of reflectance of disks in Fig. 3 reveals that with white background on shadowed side and black on illumi-

TABLE II. Effect of intensity of stimulus, reflectance of background, and depth of shadow on lightness compensation. ($W°$, degrees white in shadowed disk; $S°$, degrees white in brightly illuminated disk; F.C., apparent footcandles; Ratio, brightly illuminated to shadowed F.C.) Reflectance of white used for background and in disks = 0.80. Reflectance of black used for background and in disks = 0.03. Reflectance of gray background = 0.26.

		White background			Gray background			Black background		
$W°$	F.C.	$S°$	F.C.	Ratio	$S°$	F.C.	Ratio	$S°$	F.C.	Ratio
				A						
				Bright illuminance = 16.15 ft.-c						
				Shadowed illuminance = 0.879 ft.-c						
360	0.703	322.7	11.63	16.54	208.7	7.75	11.02	184.0	6.78	9.46
270	.536	252.0	9.20	17.16	177.3	6.62	12.35	152.3	5.81	10.84
180	.360	168.3	6.30	17.50	142.0	5.33	14.80	123.7	4.68	13.00
90	.193	74.3	3.07	15.91	84.3	3.39	17.56	60.3	2.58	13.37
45	.114	33.3	1.61	14.12	43.5	1.94	17.02	31.3	1.61	14.12
0 or 15	.026	3.5	0.65	25.00	1.0	0.48	18.46	10.8	0.81	15.58
				B						
				Bright illuminance = 16.15 ft.-c						
				Shadowed illuminance = 0.388 ft.-c						
360	0.310	302.7	10.98	35.42	178.3	6.62	21.35	126.7	4.84	15.61
270	.237	236.3	8.56	36.19	155.3	5.81	24.51	104.3	4.04	17.05
180	.160	156.3	5.81	36.31	126.0	4.84	30.25	85.0	3.39	21.19
90	.085	70.0	2.91	34.23	74.0	3.07	36.12	47.7	2.10	24.71
45	.050	31.0	1.61	32.20	38.3	1.78	35.60	22.0	1.29	25.80
0 or 15	.012	8.2	0.81	67.50	0.5	0.48	40.00	7.2	0.65	28.26
				C						
				Bright illuminance = 16.15 ft.-c						
				Shadowed illuminance = 0.009 ft.-c						
360	0.0072	92.3	3.71	515.3	67.7	2.74	380.5	36.7	1.78	247.2
270	.0055	71.7	2.91	529.1	53.3	2.26	410.9	26.2	1.45	263.6
180	.0037	47.3	2.10	567.6	37.0	1.78	481.1	16.8	1.13	305.4
90	.0020	35.5	1.78	890.0	24.7	1.29	645.0	7.2	0.65	325.0
45	.0011	25.7	1.29	1172.7	12.8	0.97	881.8			
0	.0003	17.3	1.13	3766.7	5.0	0.65	2166.7			

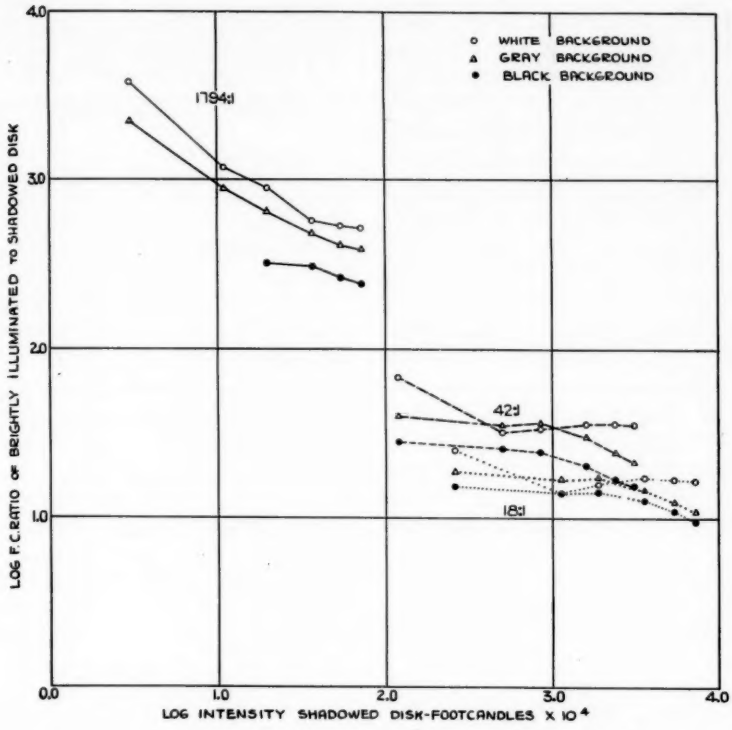

FIG. 2. Effects of background, brightness of disks, and depth of shadow on lightness compensation.

nated side, compensation is even less than with uniform black ground (cf. Tables II and III) which gives the lowest degree of compensation of the three backgrounds. Reversal of backgrounds results in higher degrees of compensation than those found with white background. Moreover, reflectance of disk has different results in the three cases: with uniform background decreasing reflectance of disk gives increasing luminance ratios; with shadowed white and brightly illuminated black grounds the luminance ratios decrease with decreasing reflectance of disk; but with shadowed black and bright white grounds these ratios increase with decreasing reflectance and there is no secondary maximum in the light gray disks as in the case with uniform white ground.

Results with the three backgrounds explain the difference in constancy effects reported by Katz and later by Gelb.[8] In the experiments of Katz the observer always sat in a brightly illuminated portion of the room when making his color matches whereas in Gelb's experiments the observers were placed in the shadowed portion. In both cases aperture matches did not match in free observation but the inequalities were different: for Katz the shadowed disk appeared too white while the illuminated disk retained its aperture character but in the Gelb conditions the shadowed disk retained its aperture appearance but the illuminated disk appeared far too black. According to Bornemeier[2] who used aperture matches for these observations as well as free vision:

"With the black background the shadowed disk appears as far too light in free vision and the illuminated disk retains its aperture appearance. This is the effect described by Katz.

"With the white background the shadowed disk retains its aperture appearance and the illuminated disk appears as far too dark. This is the effect described by Gelb.

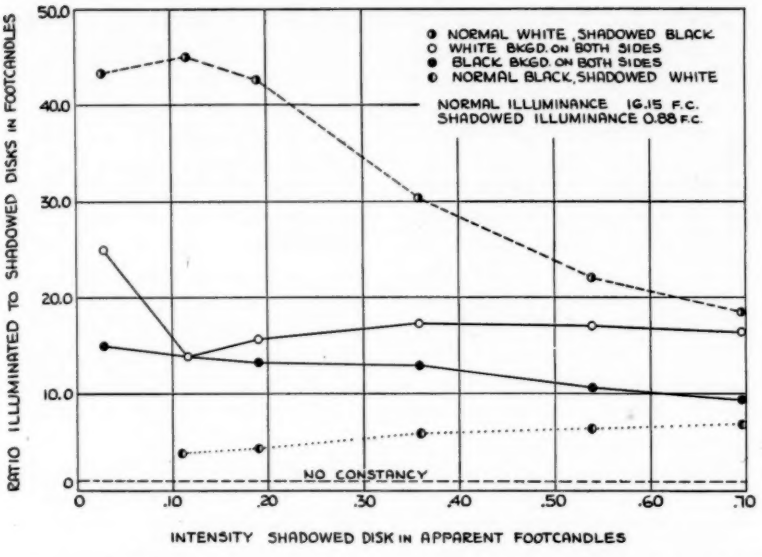

FIG. 3. Background effects on lightness compensation: by using backgrounds of different reflectances in the normal and shadowed areas it is found that amount of compensation changes radically, depending on whether white background is in normal or shadowed illumination. Greatest compensation occurs with normal white and shadowed black backgrounds.

"With the gray background the shadowed disk lightens considerably and the illuminated disk darkens. A splitting effect occurs. This latter is neither the Katz nor the Gelb effect. These relations hold regardless of the illumination conditions, for repeated efforts to obtain the Gelb effect with black background or the Katz effect with white in both illuminations used by them were unsuccessful."

The third variable, depth of shadow, also proves to have definite and important effects for compensation. Using ratios of illuminances ranging from 18 : 1 to 1794 : 1, Bornemeier found, as shown in Table II and Fig. 2, that the deeper the shadow the greater the compensation on all backgrounds. Increasing the shadow 100-fold was compensated for in roughly the same ratio as shown by the ft.-c ratios in Table II. Lowered reflectance of disk and darker shadow both work in the same direction since compensation is greater in the case of darker disks whether caused by one means or the other. The surprising thing about compensation for such dark shadows is not that objects seen in them retain their lightness character because equally great changes in general level of illumination show the same effects. The surprising aspect of compensation under these conditions is that two objects which stand in such greatly different illuminations and are compared simultaneously are said to match in lightness. The preservation of lightness quality under these conditions is striking.

It has been asserted[30] if photometric equality obtains between a shadowed white background and brightly illuminated black background that compensation for a disk in the shadowed region occurs so that it matches a disk in bright illumination sending more light to the eyes. Bornemeier found, however, that under these conditions no compensation occurs and the disk in bright illumination must be darkened to match the shadowed disk in brightness before they are judged as equal in lightness. With as little as 0.22 ft.-c difference in luminance of the backgrounds, compensation was again found with its tendency toward constancy. It appears that the results reported with "photometrically" equal backgrounds of different reflectance were due to small inequalities in brightness. Faulty measurement and failure to realize how much very small

differences in brightness of background count were responsible for this erroneous view. Compensation occurs only when the backgrounds in the two regions differ in brightness.

VI. A THEORY OF COLOR CONVERSION AND COMPENSATION

We are now in a position to see if physiological principles can explain the fundamental facts of visual compensation without recourse to psychic factors. As a result of work with non-selective samples in chromatic illuminations on various backgrounds the following principle of color conversion was formulated which applies equally well to phenomena of compensation: in every viewing situation there is established an adaptation level such that samples having reflectances above adaptation reflectance take the hue of the illuminant while samples below take the hue of the after-image complementary to the illuminant; samples near adaptation reflectance are either achromatic or very low in saturation. Background reflectance, by virtue of the large area of background and because background furnishes the border for all samples in the field, is the most important single factor in the visual field determining adaptation reflectance which is to be regarded as a weighted mean reflectance of all parts of the visual scene. This formulation embraces adaptation phenomena and contrast, the former as phenomena of level and the latter as matters of gradients from level. It requires recognition of adaptive processes much faster than those usually envisaged. Since Katz found some compensation with exposures as short as 0.0017 sec. we are justified in concluding that there is an almost instantaneous adaptive process as well as the longer, durative process commonly called adaptation. Contrast must be regarded as the establishment of gradients not with respect to reflectances of contiguous surfaces but with respect to adaptation level which tends rather to be intermediate between these reflectances.

The principle just enunciated has the advantage of providing a unitary explanation for phenomena formerly attributed to different mechanisms or mechanisms supposed to be more or less independent. It gives a reasonable explanation of the interdependence of adaptation, contrast, and compensation and the many questions raised by them. On this basis compensation occurs for very different reasons but all springing from a single source. Compensation thus may be the result of visual tolerance through shifts in adaptation level, as when a daylight blue sample is blue in green light having a blue component because the green though physically stronger is weakened by adaptation. Or compensation may arise through gradient processes, as in the case of a non-selective surface of low reflectance which is seen as black in strong achromatic illumination against a white ground or when a daylight green of low reflectance is seen as green in red illumination—in both cases the compensation is due to the fact that the samples are below adaptation reflectance and the complementary to the illuminant hue happens to coincide with daylight hue. Other cases equally common yield no compensation because the complementary happens not to coincide with the daylight hue. The change in color which actually does take place is called color conversion.[12] The effects of background, reflectance of disks, and amount and quality of illumination fit together in accordance with the above-stated principle of color conversion. Background of low reflectance induces illuminant hue

TABLE III. Effect of a divided background. Illuminance on brightly illuminated side = 16.15 app. ft.-c. Illuminance on shadowed side = 0.879 app. ft.-c. Reflectance of white background = 0.80. Reflectance of black background = 0.03. ($W°$, degrees white in shadowed disk; $S°$, degrees white in illuminated disk matching the shadowed disk; App. ft.-c, apparent footcandles; Ratio, luminance of illuminated disk to luminance of shadowed disk.)

A

Shadowed white background and illuminated black background

Shadowed white background		Illuminated black background		
$W°$	App. ft.-c	$S°$	App. ft.-c	Ratio
360	0.703	127.7	4.84	6.88
270	.536	88.0	3.55	6.62
180	.360	51.0	2.26	6.28
90	.193	11.8	0.81	4.20
45	.114	2.5	0.48	4.21

B

Shadowed black background and illuminated white background

Shadowed black background		Illuminated white background		
$W°$	App. ft.-c	$S°$	App. ft.-c	Ratio
360	0.703	360.0	12.92	18.38
270	.536	334.3	11.95	22.29
180	.360	299.0	10.82	30.05
90	.193	223.3	8.24	42.69
45	.114	135.0	5.17	45.35
0	.026	21.3	1.13	43.46

and in achromatic light samples on this ground are lighter; background of high reflectance induces complementary to the illuminant and in achromatic light its effect is to darken samples. This explains why greatest compensation ratios are found with white ground provided we recognize that the illuminated region is no less important than the shadowed for compensatory effects. Increased degrees of compensation with greater depth of shadow point to the lightening effect of low illuminations. This is in accordance with the long-established principle of opposite-sightedness in bright and dim illuminations and follows from our principle of gradient-level.

The theory proposed here implies that colors arise as gradient phenomena taken with respect to adaptation level. Reports on colors in strongly chromatic illuminants indicate that adaptation reflectance is always below the average reflectance of all objects in the field (Judd;[17] Helson[12]). For this reason a chromatic color is seen when one views a perfectly uniform surface reflecting spectrally homogeneous light. Thus on this theory there is a gradient between adaptation reflectance and reflectance of the surface even in the case of uniform fields. We have recently found that observers see a uniform, non-selective highly reflecting surface illuminated with daylight as white even in the dimmest illumination. On this theory it may be asked: How is it possible to see black with uniform, non-selective low reflecting surfaces since the surface is above adaptation reflectance and should therefore yield a "white"? However, a strictly uniform surface cannot be perceived as a surface and approximations to such a surface do not yield as good a black as the blacks which are aided by gradient effect or contrast, as is well-known. Irregularities in approximately uniform surfaces furnish the negative gradients by which such surfaces appear black. This brings us to the role of gradients in the visual field.

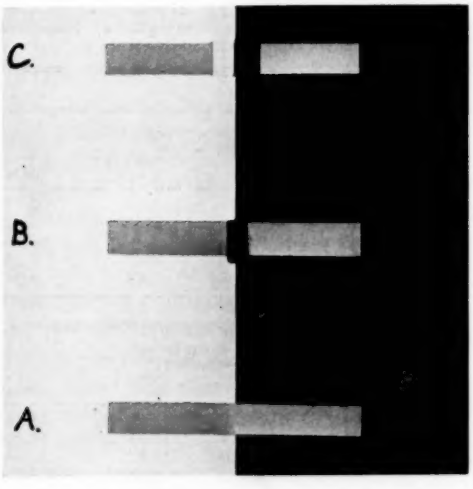

FIG. 4. Effects of boundaries in preventing spread and aiding contrast-gradient.

It has been customary by some workers in vision to regard only the colors associated with positive gradients, those above adaptation level, as "real" and to assign those arising from negative gradients to the eye or the mind. If, as the facts of compensation and color conversion imply, all colors must be regarded as gradient effects within the visual mechanism, the distinction need not be made. It is commonly thought that "black" is the color *par excellence* due wholly to the eye. As a matter of fact any hue, in all saturations, can be evoked either from positive or negative gradients: in spectrally homogeneous yellow illumination samples of high reflectance are yellow while those of low reflectance are reddish-blue, the former a result of positive gradient, the latter of negative gradient; but in spectrally homogeneous blue illumination samples of high reflectance are blue and those of low reflectance are reddish-yellow as a result of reversal of gradients in the two illuminants. The colors arising from either positive or negative gradients are equally good, the latter often appearing more saturated in strongly chromatic illumination than the former.

VII. CONTOURS, BOUNDARIES, AND TRI-DIMENSIONAL EFFECTS

So far we have dealt mostly with cases that seem to offer less difficulty for physiological explanations than certain crucial phenomena which have been offered as requiring other types of explanation. Let us see what we can do with them. A black disk illuminated by a spot-light appears as a white, luminous object until a small piece of white paper is brought near when it turns black with startling rapidity (Gelb[8]).

The converse effect can be demonstrated by shadowing a white disk and leaving the rest of the surroundings brilliantly illuminated. The disk appears black until displacement of the shadow so that its penumbra becomes visible causes the disk to appear as "white-in-shadow" (Kardos[20]). It has been denied (MacLeod[30]) that contrast mechanisms could account for these effects because of the great difference in size between the areas involved. But triggering effects are not unknown in the domain of physics and chemistry. The inequality in magnitudes of the terminal members of the gradients and the rapidity of the changes imply that the visual mechanism is capable of triggering effects. This assumption is consonant with what is known about retinal interaction, the rapid establishment of initial adaptation level, and the great importance of borders and contours.

The effects of boundaries on colors were noted in compensation phenomena as well as long before on contrast. Hering pointed out that a shadow may be seen on one's sleeve as either a stain (surface color) or as a shadow thrown on the cloth (modification of the illumination). If a dark line is drawn around the shadow it becomes a thing and, apparently contrary to contrast effect, darkens. Change from one to the other appearance is accompanied by changes in texture, transparency, and tri-dimensional localization of the color. Here we touch upon the relations between spatial and color effects. Katz[21] found that as he approached a white disk behind a rotating sectored disk, the white disk grew lighter and retreated in the third dimension. MacLeod[30] also found greater compensation with space-filling shadows than with cast or bi-dimensional shadows.

Some suggestions toward including these spatial effects within the general framework of retinal processes may be ventured as follows. Along with gradient processes which accentuate differences within the visual field go assimilative or inductive color processes which tend to obliterate differences through spread. Contours and boundaries tend to restrict spread within a figure but often boundaries are nullified as induction forces its way across lines of demarcation. Spread within an object is seen in Fig. 4 wherein the lowest gray bar, *A*, shows little or

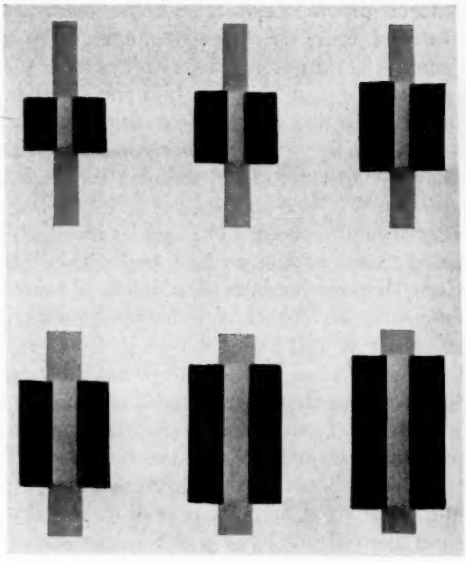

FIG. 5. Relative absence of contrast due to assimilation within central gray strips and Newhall's reversal of contrast effect due to induction from black surround.

no contrastive lightening or darkening effect from the black and white surrounds respectively. Some contrast effect is seen in the middle bar, *B*, with one boundary and more is apparent in bar *C* with the double boundary which better segregates the two parts of the figure so that spread within the figure is prevented and each part is more amenable to gradient influence from the surround.

Inductive effects across boundaries giving rise to assimilation are found in Fig. 5. While examining these figures for the levelling effects of color induction Newhall's reversal of contrast effect[32] was found. Here grays surrounded by larger areas of black are *darker* than those with smaller black surrounds. Furthermore, assimilative effects appear also within the grays since little or no lightening gradient is visible at the black borders. We thus find inductive, assimilative, and gradient effects coincident with contour and boundary phenomena which are important in bi-dimensional organization of visual fields. We turn now to tri-dimensional problems.

In what way can processes of spread, assimilation, and induction help clarify tri-dimensional color effects? Contrast gradients, especially of

brightness-differences, establish the boundaries between objects and their surroundings. To see objects in the third dimension requires separation of planes and formation of borders. Gradients help in separating objects from surrounds and spread within figures makes for figural unity since similar parts tend to form units as Wertheimer has shown.[38] It was pointed out that drawing a border around a shadow changes its localization from in front of the surface to "within" the surface. Here the presence of well-defined contour is accompanied by change in tri-dimensional localization as well as by change in lightness of the shadow. So long as the shadow has the fuzzy, indefinite edges characteristic of its penumbra it is localized in front of the surface and appears transparent; when the penumbra is replaced by a well-defined border the shadow takes the plane of the surface and becomes part of it. But these are not the only ways in which brightness and chroma differences contribute to tri-dimensional spatiality in vision.

Colors also possess inherent spatial properties inseparable from contour and boundary effects and just as important for organization of the visual field. Ames[1] has generalized these properties as follows: (1) cold colors appear more distant than warm; (2) weak chromas appear more distant than intense chromas; (3) values near background value are more distant than high or low; (4) soft edges appear more distant than hard edges; (5) depth effect may be achieved by overlay (interposition); (6) depth may be obtained by accent; (7) dark objects with blue edges appear more distant than those with red edges. Substantiating the distinction between warm and soft colors, Koffka and Harrower[24] refer to red and yellow (warm colors) as advancing and to green and blue (cold colors) as retreating. These writers show that the hard colors, red, yellow, and white, have greater organizing power than the soft colors, green, blue, and black. The former give evidence of greater visual acuity than the latter because of their hard boundaries which enable observers to separate them more easily. Hard colors on hard grounds give greater acuity than soft colors on soft ground, according to the same investigators.

The inseparability of chromatic and spatial effects in vision needs no argument for vision serves to acquaint us not only with color but with form, size, distance, and tri-dimensionality of objects as well. Assimilation within a figure tends to give it internal unity and gradient between it and its ground serves to demarcate it from other objects. The processes of adaptation, contrast, induction, and assimilation which have usually been regarded as contributory only to color effects are thus seen to be no less important for the spatial characteristics of vision. The preservation of lightness serves to demarcate the object from its surround and to make it a thing just as much as it tends to "color constancy."

It is thus seen that color processes play a double role in the color-space functions of vision: they contribute the matter or stuff of the visual field and at the same time determine the way in which the field is organized both bi-dimensionally and tri-dimensionally. Which is to be regarded as primary, color or space, it is too early to decide but the evidence now at hand points to the increasing recognition of the importance of color for spatial discriminations. Color compensation by yielding approximate color constancy thus aids in the production of a stable visual world not only through preservation of color as such but just as much through preservation of spatial organization which is largely due to the color processes of the eye.

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The numbers in parentheses correspond to the reference numbers used in the text. For more extended bibliographies consult Helson,[12] Judd,[17] and MacLeod.[30]

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The Farnsworth-Munsell 100-Hue and Dichotomous Tests for Color Vision*

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THE F-M 100-hue test is a simple exploratory technique for the laboratory examination of color vision. It yields data from which other tests can be constructed; one of these, a screening or sampling test which dichotomizes subjects into two discrete classes of color anomaly, is described in the second part. The principles upon which these tests are constructed are described and preliminary results are given.

I. F-M 100-HUE TEST

1. Construction of the Test

The purpose of the test is to measure hue discrimination in a curve of constant value and chroma and thereby indicate the distortion of the chromaticity plane of anomalous vision as compared to normal. An exploratory study of normal and anomalous color vision should be planned independently of any theory and should meet at least two additional requirements: (1) The test materials should sample all the visual hues and (2) they should be quantified according to accepted color specifications. If the test is to receive general usage it should be inexpensive, reproducible, and transportable. The Munsell 100-hue series of colored papers described in a previous issue of the journal[1] was found to meet these requirements and was fairly well spaced perceptually. Gross inequalities in discriminative differences were eliminated by dropping from the series one of each pair of papers which was most often confused by normals as rated on standard tests for color vision. Eighty-five colored papers were found to be about equal in chroma and value for normals and each was perceptably different in hue from its neighbors.† Some of the steps were more easily noticeable than others so that the whole circuit of colors was estimated to embrace over 90 J. E. N. D. (Just Easily Noticeable Differences) under the conditions of observation described in Section 2, "Test Method."

It was possible to construct a simple projective transformation of the I. C. I. and Standard Observer Diagram upon which the 85 colors would plot in a remarkably good circle (Fig. 1) corresponding to their subjective appearance. To bring the entire chromaticity plane into line with other observed data the diagram in Fig. 1 was plotted with the point representing Illuminant *C* at the center of a polar log graph in which $x = y^2$ (Fig. 2). The two processes of conversion represented a purely empirical transformation achieved by trial and error in order to represent best all of the three following types of subjective data available from the test materials. First, the complementaries within the 10 principle Munsell papers were carefully matched under an illuminant slightly yellower than *C* with the Atlas Neutral at Value 5; one indication of the validity of the transformation is the close grouping on the diagram of the dots which represent mid-distances between the positions of the complementary colors. Second, the apparent

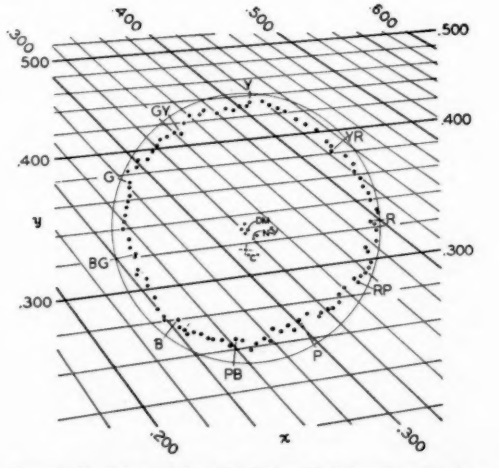

FIG. 1. Position of the 100 Munsell Color Standards at 5/5 on a perspective projection of the I.C.I. Standard Observer Diagram.

* Paper presented at Symposium on Color-Blindness at the meeting of the Optical Society of America, March 4–6, 1943, New York, New York.

[1] Dorothy Nickerson and Walter C. Granville, J. Opt. Soc. Am. **30**, 159–162 (1940).

† While 85 papers constitute the present form of the test further efforts to smooth the series will change the number. Therefore, the number in the basic series is retained in the name of the test.

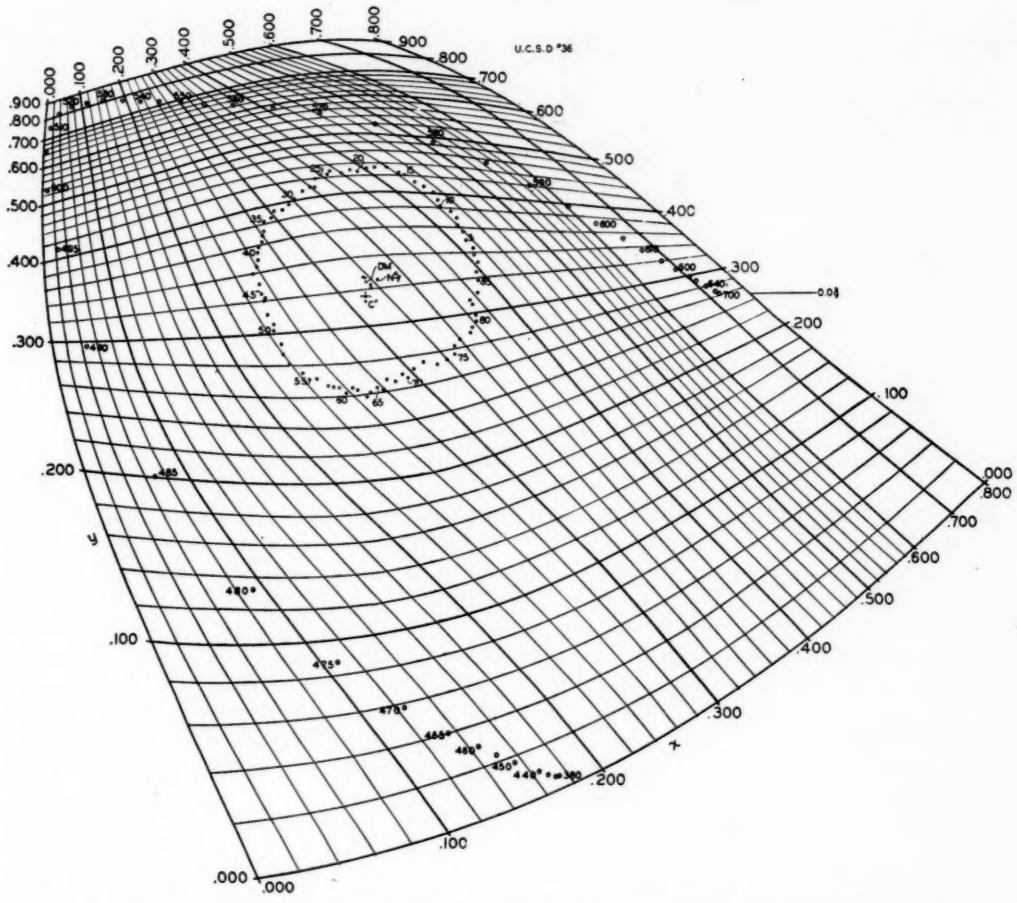

FIG. 2. Perspective projection plotted on a polar log system to produce a Uniform Chromaticity Scale Diagram. Dots show position of the 85 colors selected for the test.

equality of chroma is indicated by the nearly equal radii between each color and the average disk mixture point, DM in Fig. 2, which is taken as the center of the series. Third, the scale distances between the colors are shown in Fig. 3 to have good general inverse correspondence with the errors of 200 observers rated as normal on standard tests and who in addition did not make over 12 errors when arranging the entire series.

We may assume, then, that the Uniform Chromaticity Scale Diagram (U. C. S. D.) in Fig. 2 represents a fair spatial generalization of the appearance of colors near the position of the 100-hue series from which the test was constructed. While it is offered as a preliminary diagram it is of sufficient accuracy to interpret the distortion of chromatic sensitivity in anomalous vision.

2. Test Method

For test purposes the 85 colored papers are mounted in dull black Bakelite caps which expose a disk of color $\frac{1}{2}$" in diameter sunk $\frac{1}{8}$" below the rims which are slightly more than $\frac{1}{8}$" wide. The backs of the caps are numbered in consecutive order. The series is divided into four equal parts which are placed in matt black panels. Each quarter-series is mixed in random order and presented for the Subject to "arrange

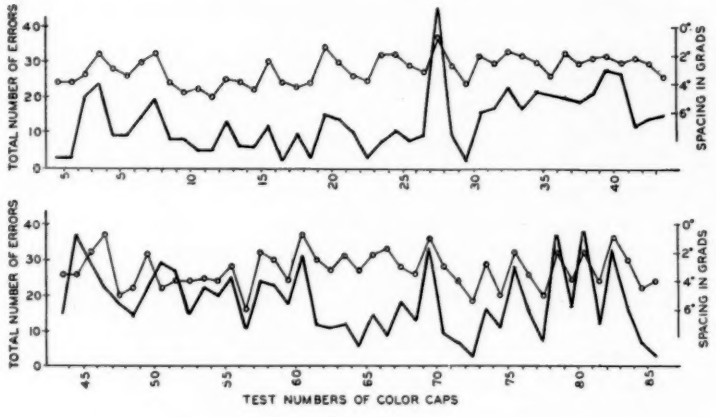

FIG. 3. Observers' errors plotted against the angular distribution of the 85 selected colors on the U. C. S. D. 212 trials. -o-o-o- spacing: ——— errors.

in consecutive color order" or a "smooth color series" between terminal colors which are fixed at either end of the panel. All data were taken under Macbeth Illuminant *C* lamps.

Norms are developed from the scores which a *S* makes in assigning positions to the colors in the series. The error score for each color cap is computed as the sum of the differences between the number of the color cap and the numbers of the 2 caps placed adjacent to it. Figure 4 shows a section of a sample scoring sheet. Radial lines are given the numbers of the color caps, circular lines are abscissae upon which the error scores are plotted. The first, inner abscissa is numbered 2, the lowest possible score and the one which represents perfect serial order. A simple transposition in the position of two consecutively numbered caps results in four scores of 3 each—the lowest possible error score. The plotted points are connected to show the profile clearly.

3. Classes of Color Vision

(1) About four-fifths of an adult male population makes fewer than 12 transpositions, most of which are simple, 2-cap exchanges. These errors are random, seldom reoccur on retest and are not bunched in any one region. Such *S*'s are considered to be in the normal range of color vision and this rating is confirmed by other tests. Typical scores of a normal *S* are shown in Fig. 5. Between these *S*'s and the following class the line of distinction is arbitrary.

(2) About one-tenth of a male population makes more than 12 transpositions and their error scores may reach 6 or even more, but the errors do not group in any region. On lantern tests designed for the detection of color blindness these *S*'s may confuse adjacent colors such as light blue and green but do not confuse complementary colors. Some have difficulty in reading pseudo-isochromatic plates, but never give color blind responses on so-called diagnostic plates. It is apparent that their hue-difference limens are high as compared to the 80 percent making less than 12 transpositions but that there is no color imbalance in their vision as compared

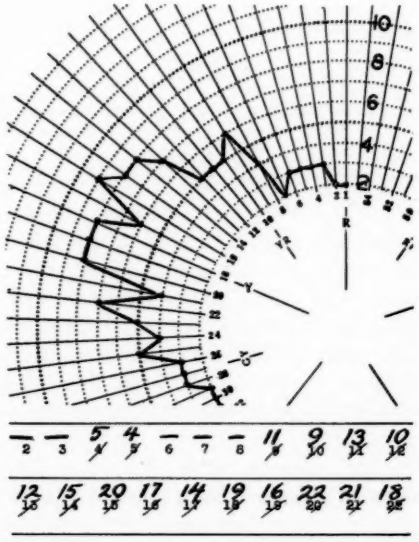

FIG. 4. Section of a subject's profile illustrating how error scores are plotted.

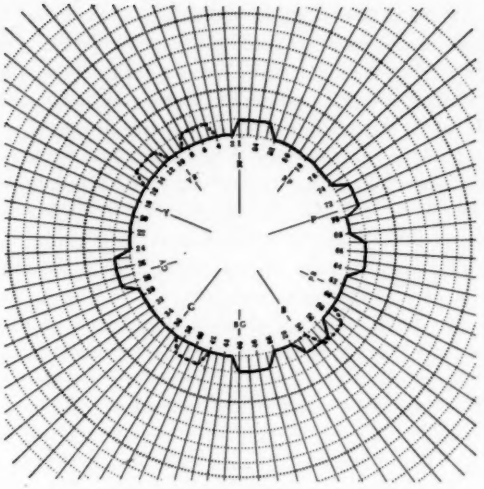

FIG. 5. Typical color-normal profile. 2 trials. Figs. 5 to 9 illustrate specimen profiles of 5 classes of color vision obtained on the F-M 100-hue test.

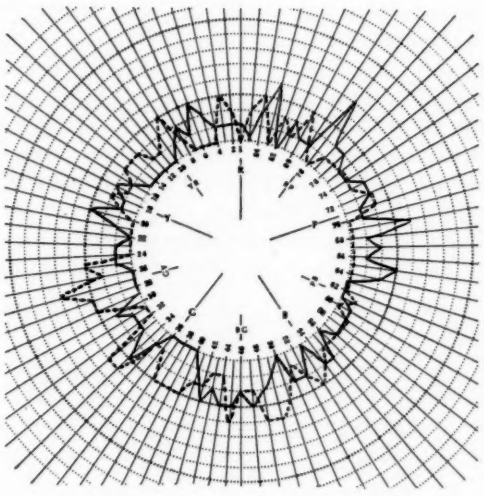

FIG. 6. Specimen of low discrimination profile. 2 trials.

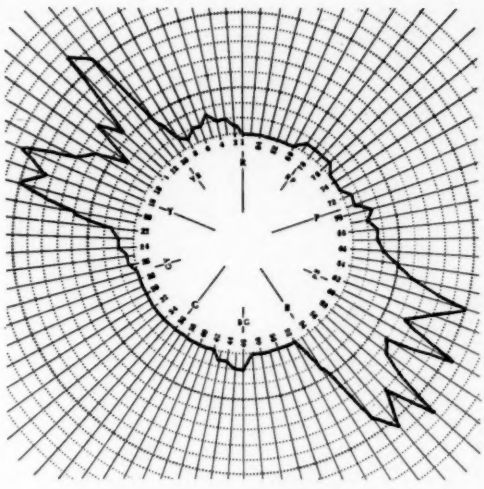

FIG. 7. Specimen of deuteranomalous profile. Average of 2 trials.

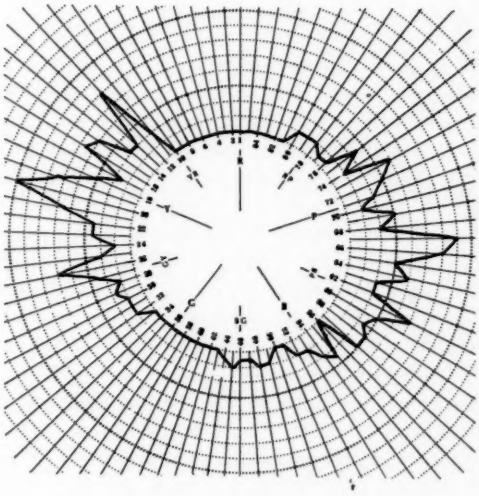

FIG. 8. Specimen of protanomalous profile. Average of 2 trials.

with normals. Their color vision may be represented by the U. C. S. D. in Fig. 2 undistorted but scaled in large limen units. These *S*'s have *low discrimination* and typical of them are the 2 profiles from one *S*, shown in Fig. 6, who is a trained color-worker, cooperative and well motivated. Thus, inexperience, indifference or color-ignorance does not account for this type of score.

(3) The profiles of color anomalous *S*'s show maximum errors in two regions which are nearly opposite. The regions are defined numerically as the points at which the means of the error scores occur. These two points and the point representing Illuminant *C* place the major axis of a *S*'s chromaticity plane.

Anomalous Subjects so far examined can be reported into three classes. The major axis of

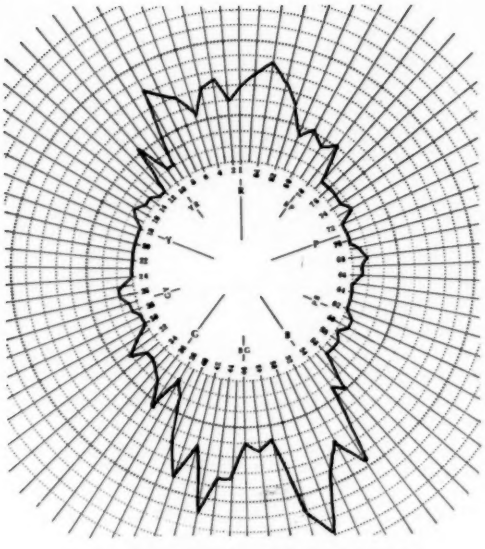

FIG. 9. Specimen of tritanomalous profile. Average of 2 trials.

about half the anomalous *S*'s is near the 15th color cap (reddish Yellow) and the 59th (purplish Blue) color cap (Fig. 7); these are diagnosed by most other tests as deuteranomalous. Nearly half fall near the 19th (Yellow) and 65th (bluish Purple) colors; these are diagnosed by most other tests as protanomalous (Fig. 8). A few *S*'s exhibit maximum errors near the 1st (Red) and 46th (Blue-Green) color caps (Fig. 9). These are diagnosed by most other tests as tritanomalous or blue-yellow blind. The trichotomy in color visual anomaly is clearly indicated in Fig. 10, where the axes of the first 32 *S*'s examined, whose deficiencies were found sufficiently pronounced to be positively identifiable, are plotted for inspection.

4. Interpretation of Data

The means of the individual error scores are assumed to occur at the points of maximum tolerance or minimum discrimination in a direction tangential to the color circle at the point where the mean occurs. This is substantiated by the gradual increase in accuracy in the arrangement of color caps further removed from the poles of the major axis until the 90° region is reached where hue discrimination usually approximates normal.

If these directions of reduction of discrimination are assumed to hold in a general way for the whole chromaticity plane we can assume the central axis of reduction of chromatic discrimination through the point representing Illuminant *C* to be parallel to or intermediate in direction between the lines which are tangential to the points of mean errors. These are indicated by the dot-dash center lines in Fig. 11 and designate the principal minor axes, or axes of minimum discrimination, of each class of color anomaly.

Any particular case of anomalous vision can be usefully visualized as a tilting or foreshortening of the normal U. C. S. D. Then the U. C. S. D. of a moderate case of red-bluegreen or protanomalous vision would have the shape of *a*, Fig. 11; the vision of a nearly complete protanope would be represented by *b*; an extreme case of deuteranomalous vision is represented by *c*; and tritanomalous vision by *d*. The same psychological scale of units would apply to all diagrams and each would represent the particular U. C. S. D. of that case of anomaly. Figure *a*, for instance, would represent an individual whose minor axis is reduced by three-fourths; any two colors which lay parallel to the major axis would appear to this subject as much alike as two which were separated by four times this distance on the minor axis or a parallel to it.

The above analysis has been presented as a convenient method for the visualization of

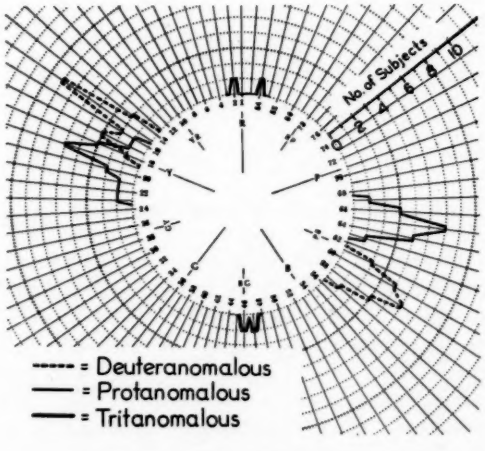

FIG. 10. Distribution of mean errors from 32 color-anomalous subjects.

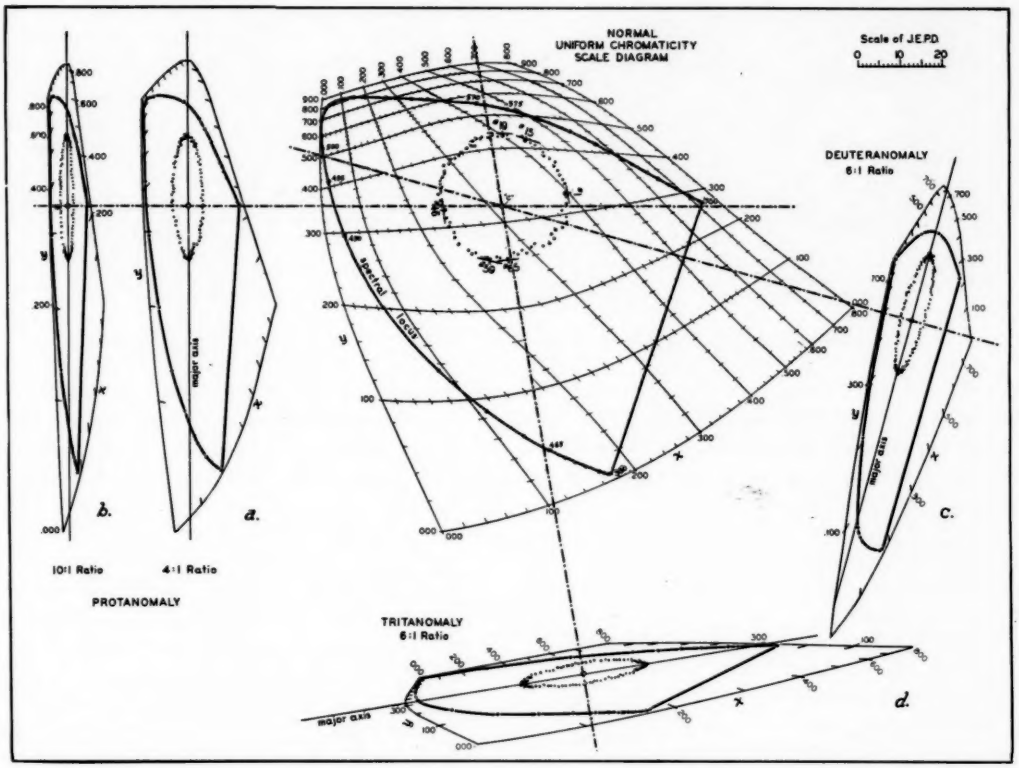

FIG. 11. Diagram illustrating theoretical reduction of the normal Uniform Chromaticity Scale Diagram for various axial ratios of the three types of color anomaly. Dots indicate position of the 85 selected colors.

anomalous color vision. It is, of course, an oversimplification and will be modified in many ways by new data. But even if our state of knowledge permitted a more accurate analysis of anomaly it would still present a highly useful working method.

5. Uses of the Test

1. Classificational

More than one hundred cases of color anomaly have been studied at the NYU Vision Laboratory with the 100-Hue Test, exclusive of mildly anomalous cases whose deviations were too weak and scattered to classify. All fall within one of the three classes named in Section 3, paragraph 3. So far as can be determined, not one case of so-called "red-green" blindness has been examined, nor any other combination of these three classes. The fact that they have not so far been found does not exclude the possibility of rare anomalies being discovered by this test.

2. Individual Analysis

The diagnostic function of the test in analyzing individual cases of color weakness and color anomaly has been suggested in Section 3 above. More data must be accumulated before it will be possible to state the probable reliability of a trial and calculate the degree of anomaly from the distribution of errors.

3. Check on Significance of Responses

An example of its use in analyzing test responses is furnished in the New London inves-

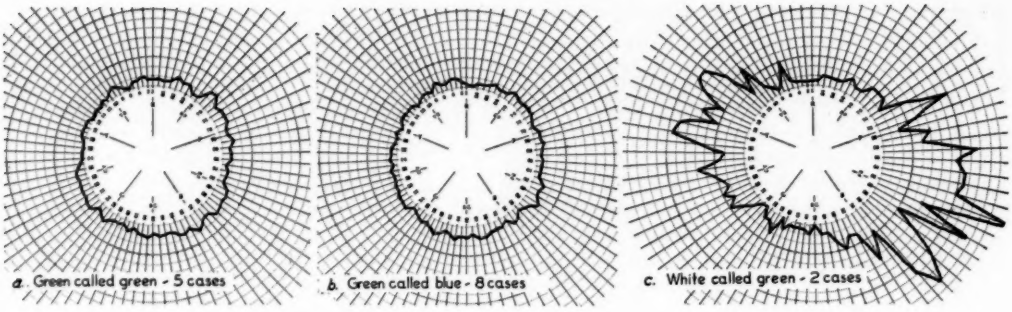

FIG. 12. Responses to Canadian Lantern colors compared with subjects' profiles on F-M 100-hue test.

tigation of the Canadian Color Lantern.[2] The question arose as to the significance of the reply "blue" to a filter which was described in the lantern manual as "green." Did this response indicate an anomaly or difference in visual response or merely a difference in terminology? Figure 12 is reproduced to show that the distribution of the errors in the 100-hue test of the group of *S*'s who called the filter "green" is normal and the same as the distribution of errors of the *S*'s who called it "blue" and consequently either reply should be acceptable. However, in Fig. 12, *c* the response of "green" to "white" is shown to be diagnostic of anomalous vision.

4. Check on Test Validity

Certain aspects of validity in other color tests can be checked by the use of observers whose major axes have been determined with the 100-hue test. The instructions accompanying the American Optical Company reprints state that yellow-blue blinds read "confusion" figures in plates 23, 24, and 27 to 30, yet two tritanomalous *S*'s in the NYU Vision Laboratory whose major axes were found to be between color caps 84–2 and 46–47 gave the normal responses to these plates without hesitation. The six Stilling plates in groups XIV and XV, 1929 edition, were about half misread but normals often give anomalous responses on these plates. The two Rabkin plates which, according to the instructions, "tritanopes do not see" were read normally. This indicates that these plates are invalid for the detection of tritanomaly, at least of this class so far as studied by us. Other uses for the 100-hue as a reference standard are found in the New London Study of the AO Pseudo-Isochromatic Plates.[2]

5. To Check the Results of Remedial Treatments

A *S* who takes large doses of Vitamin A and makes regular attempts to read the AO plates may in time succeed in reading most of them correctly, but this success is not proof that his color vision has improved and that he is fit for service in war or industry. A partial restoration of one of the elements of vision would, however, be expected to result in improved discrimination and a changed profile in the 100-hue test. Beyond the customary small practice improvement neither vitamin administration nor monochromatic excitation as given at the NYU Vision Laboratory to 24 *S*'s have been succeeded by a change in the test profile.

6. As a Basis for the Construction of Special Tests

The principle of the Uniform Chromaticity Scale Diagram in Fig. 2 is that equal space distances represent equally perceptible color differences. To the extent that the diagram is a correct reflection of the data derived from the 100-hue test it will enable us to predict the degree of apparent likeness or unlikeness of any two colors to a normal or to any class of color anomaly to any degree of that anomaly as compared with the normal. We need only to redraw

[2] John David Reed under the direction of C. W. Shilling, Commander (MC) U.S.N., Medical Research Laboratory, U. S. Submarine Base, New London, Connecticut, "Preliminary Report on Color Vision Testing," Sept. 12, 1942 and "Report on Trial of Royal Canadian Navy Colour Vision Lantern in Comparison with Other Tests of Color Vision," Jan. 18, 1943.

the normal U. C. S. D., with major to minor axis of the ratio desired, plot the x–y coordinates on the condensed diagram and scale the relative likeness-unlikeness relations of particular colors with a linear scale.

This method can be used to explain the diagnoses made by existing pseudo-isochromatic plates, to construct new ones, or to construct tests on entirely new lines. An example of this technique applied to a particular industrial problem, with a new methodology, is given in Part II.

II. DICHOTOMOUS TEST B-20

The Dichotomous test, B-20, was created to meet the particular problem of the personnel department of a transformer manufacturing corporation but the need was similar to that of every company hiring workers who would be required to distinguish code colors with certainty.

The requirements of the test were: that it should be capable of very rapid administration, immediate interpretation without ambiguity,

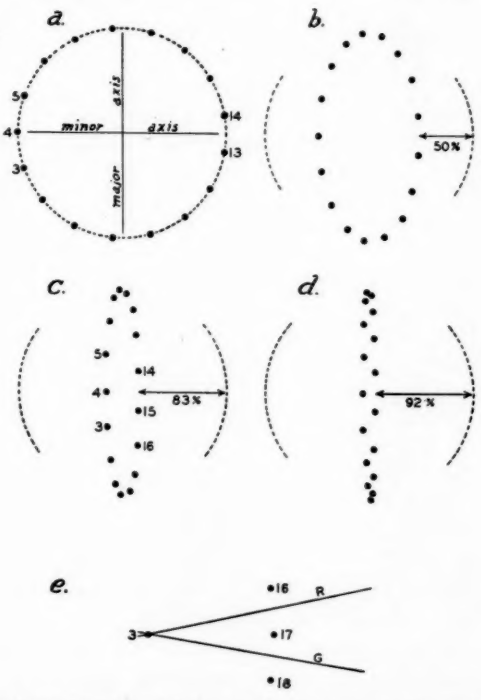

FIG. 13. Principle of color association accompanying axial reduction of the chromaticity plane.

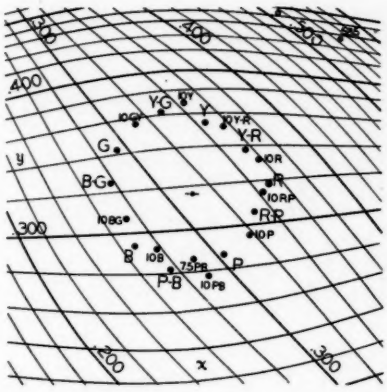

FIG. 14. Position of the colors selected for the Dichotomous Test B-20 on the U.C.S.D.

that it should dichotomize the S's into "pass" or "fail" classes, and that the dividing line should be at a point which would fail only those who would possibly be unable to distinguish the particular code colors used by the company. This last criterion would admit individuals who would make many errors on such pseudo-isochromatic tests as the Ishihara and AO.

Any screening test of color vision is a kind of "trick"; it is a device which takes advantage of some weakness which characterizes the color anomalous. The weakness which it was decided to capitalize on for this test was the lineality in appearance, of what, to a normal, is a circuit of hues. This suggested a set of color caps which people of each class of vision, normal and anomalous, would arrange in a different and characteristic order.

Standard Munsell papers were then studied from the viewpoint of the following test requirements.

(1) The saturation should not be high enough to permit the factor of hue recognition in color experienced applicants to interfere with apparent serial arrangement according to hue.

(2) It is desirable that there be a red of somewhat higher value (brightness) which the protanomalous can include in his series with satisfaction.

(3) Spacing of hues in the bluish green and in the purplish red region should just about equal the angular difference between the axes of reduction of the two common classes of anomaly as

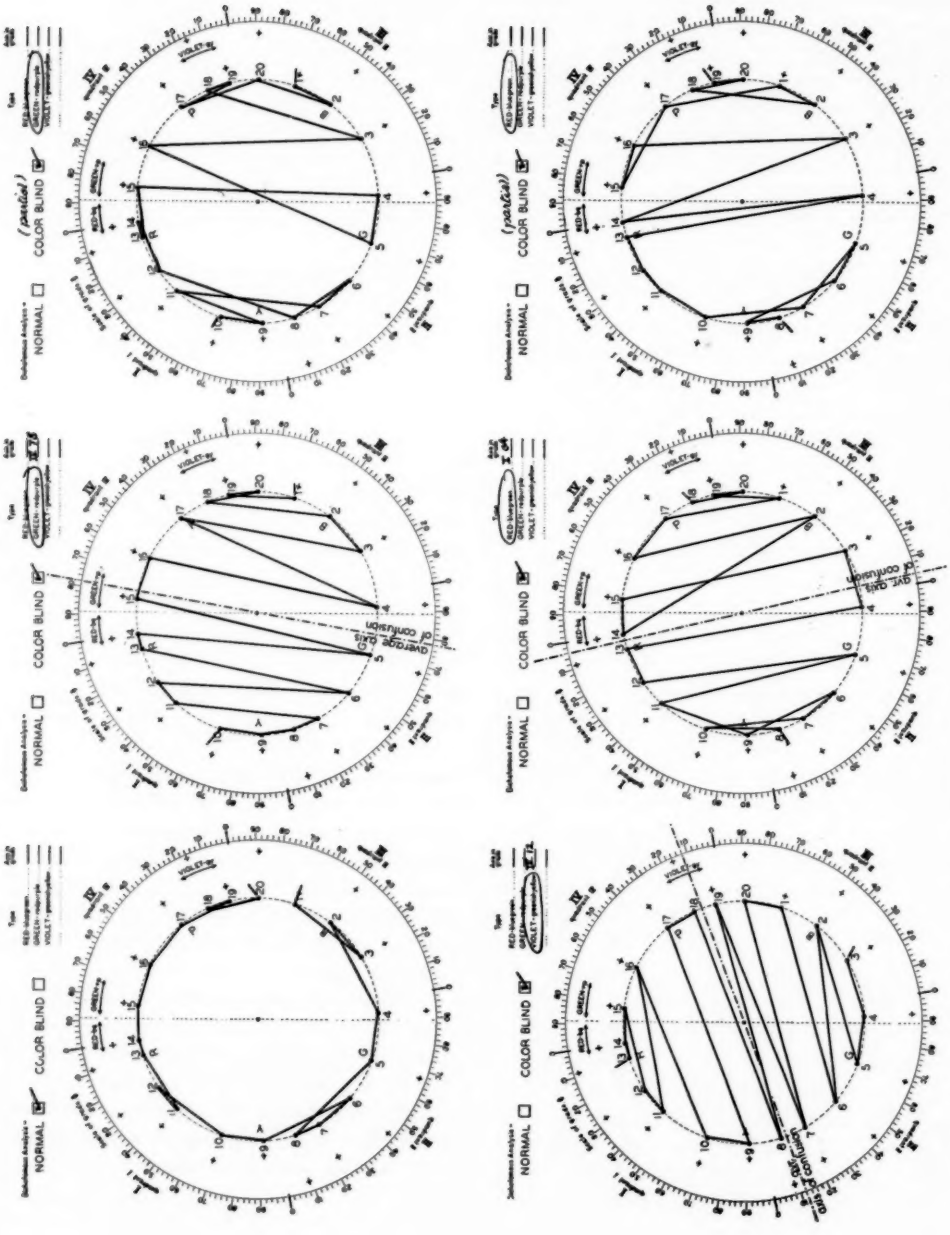

FIG. 15. Specimen profiles obtained from the dichotomous test.

explained in principle in the following paragraph. This is to make possible a series which seems satisfactory to the individual in each class of vision and also permits ready classification by the examiner.

If in *e*, Fig. 13, we construct lines *R* and *G* through a given color point parallel to the protanomalous and deuteranomalous minor axes and let the colors on the opposite side of the circle be selected at points between these lines, the two classes will be readily distinguished by the order of arrangement they make. The protanomalous (red-bluegreen confusing) will set the colors in a 16, 3, 17 series; the deuteranomalous (green-redpurple confusing) will set the colors in a 17, 3, 18 order.

(4) Spacing of colors should be such as to suggest cross-circle matches to the anomalous *S* with an 83 percent reduction of the minor axis. This was determined in the following way:

In the description of the 100-hue circuit it was estimated that there were over 90 J.E.N.D.'s around the circle which would make the radius consist of about 15 J.E.N.D.'s ($90 \div 2\pi r$). Since there are 5 Munsell chroma in this 15-J.E.N.D. radius, 1 average chroma step = 3 J.E.N.D.'s under the conditions of observations. Inspection of the code materials (braid wrapping on wire) indicated that no discrimination would be required for less than the equivalent of two chroma steps; therefore 6 J.E.N.D.'s were selected as the psychophysical unit of measure in the following analysis.

In anomalous vision, colors which are $6x$ J.E.N.D.'s distant on the minor axis appear as alike as colors which are x J.E.N.D.'s distant on the major axis when the ratio of the two axes is approximately 1 : 6 (83 percent reduction). When the ratio is greater, not only would the $6x$ J.E.N.D. distant colors appear more alike than the x J.E.N.D. distant colors but 6 J.E.N.D.'s on the minor axis would not constitute a surely discriminable difference. This is the indicator employed in the dichotomous tests. x can have any value greater than 1 but the separation of hues in the chosen color circuit should approximate one-sixth of the diameter of the circuit.

Normals arrange such a series in approximately circular order, as indicated at *a*, Fig. 13. Even a *S* with axial reduction of 50 percent finds the circular order satisfactory as is apparent from *b*, Fig. 13. But when the minor axis is decreased to about 16 percent it is evident from *c* that colors 4 and 15 are spatially as close as 4 and 5, and, if our U. C. S. D. is approximately correct, will appear perceptually as close and hence as good an order as a 4, 5, . . . 15, 16 series. Any reduction greater than this, as in *d*, will obviously call for a cross-circle arrangement throughout, which will appear to be the only possible linear series, and a very satisfactory one, to a highly anomalous *S*.

From an examination of the Munsell series of forty papers available at 5/2 it was possible to select 20 papers which would approximate these requirements, when $x = 2$. Their position is shown on the U. C. S. D. in Fig. 14 plotted from spectrophotometric data and calculations furnished by Dorothy Nickerson. Papers were inserted in the Bakelite caps described in the first part of the paper, and were presented, mixed in random order, to the *S*'s with instructions to arrange them in a regular color series.

Typical test results are shown in Fig. 15 with profiles made by drawing lines which connect the numbered dots on the score sheet in the order in which the color caps were arranged. The dots approximate the true positions of the color capsules on the U. C. S. D. which are shown by crosses. The average inclination of the series of connecting lines may be scored in grads (= ĝ, 100 divisions to a quadrant) for correlation with other tests. For industrial use the accepted and rejected classes are called "normal" and "color-blind," respectively. Counter-clockwise inclination of the axis indicates red-bluegreen blindness (protanopia); clockwise, green-redpurple blindness (deuteranopia); more horizontal matches indicate violet-greenishyellow blindness (tritanopia). Normals make few or no transpositions and always set up a generally circular order; all subjects whose order of choice results in a profile that criss-crosses the center are dichotomized as color-blind.

SUMMARY

The F-M 100-Hue Test has been described as a laboratory device for the analysis of color anomaly. It has been shown that color anomaly can be represented as a simple foreshortening of the U. C. S. D. of normal vision and the various

kinds classed according to the axis of greatest reduction in color perception. The results also show that there is a class of people who have low discrimination without imbalance of color perception.

New types of tests can be created from these data for specific purposes. One, a "Dichotomous Test" has been prepared for code-color discrimination and its value has been indicated. Critical scores for such measures can be determined for particular occupational requirements. This is not possible with general tests for color anomaly.

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These studies would not have been possible without the long-continued interest and encouragement of Professor Douglas Fryer and Professor Edwin R. Henry who have put the full resources of the Psychology Department at the author's disposal and have eased every difficulty with advice and encouragement. Nor could these tests have been developed without the cooperation of many members of the Inter-Society Color Council; and particularly of Miss Dorothy Nickerson and Dr. Deane B. Judd.

Book Review

Vertebrate Photoreceptors. SAMUEL R. DETWILER. Pp. 184; Figs. 110. Experimental Biology Monographs, The Macmillan Company, New York, 1943.

It is a welcome coincidence for those interested in the vertebrate eye and its mode of functioning that three books (Polyak's *The Retina*, Wall's *The Vertebrate Eye* and Detwiler's *Vertebrate Photoreceptors*) have been published in this country in the past three years. Since these all differ in scope and treatment of material each one is a valuable addition to the literature on the eye.

Professor Detwiler's book follows the plan of the editors of Experimental Biology Monographs which is to present factual summaries of recent advances in research and to show the theoretical implications of such advances. The author was well qualified to do this for the vertebrate retina, for he has had an active and enthusiastic interest in its structure and function since 1916.

Following a general introduction to the vertebrate eye and retina the author discusses the structure and development of rods and cones without going into minute cytological details. Next is a chapter on retinal structure in relation to nocturnal and diurnal modes of life. One of the remarkable adaptive features of the retina is seen in the relation of the dominant type of visual element to habit. While most vertebrates possess both rods and cones, some, which are active only during the day, have a pure cone retina, while others, which are active only at night, have only rods. Two chapters are devoted to photomechanical responses in the retina. These responses include the movement of pigment within the pigment epithelial cells (a phenomenon which probably does not occur in mammals, including man) and the movements of rods and cones under the influence of daylight and darkness. In spite of much work the significance of the changes in position of the rods and cones is not fully known, neither are the factors which influence the contraction and elongation of the rod and cone myoids. The size, number and distribution of the visual elements in relation to visual acuity is discussed.

In his treatment of the fovea, Professor Detwiler criticizes, with apparent justification, G. Elliott-Smith's contention that the changes which have occurred in the parts of the anthropoid brain concerned with vision were due to the origin of the macula. Concerning the functional significance of the fovea it is apparent that the author favors the recent theory of Wall's—that the fovea broadens the retinal image, rather than the older view that the fovea has developed to allow light to fall directly upon the photoreceptors, without passing through all the layers of the retina.

A discussion of retinal photopigments, especially the rhodopsin and porphyropsin cycles of Wald, provides a background and satisfactory interpretation for the behavior of Kolmer's droplets, which have interested Detwiler for some years. This is a remarkably good instance of biochemical information supplying an explanation for histological findings.

The final chapter, except for a brief recapitulation, deals with vitamin A deficiency and the retina. A discussion of the effects of vitamin A deficiency on visual thresholds again provides a good background for the studies on retinal degeneration, begun by Tansley and continued by Miss Johnson. Recently it has been shown that, following striking degeneration of the retinas of rats on a vitamin A deficient diet, the restoration of adequate amounts of this vitamin results in the slow regeneration of new rods provided their nuclei had not degenerated. It is suggested that the long period often required by humans to recover normal vision after vitamin A depletion may be due to partial degeneration and subsequent slow regeneration of the visual elements.

The reviewer found the book most readable and, having had experience with the difficulty of making good histological preparations of the retina, the good illustrations of the author's preparations added much to its attractiveness.

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